

Semen Uimonen

Energy Consumption of Escalators

School of Electrical Engineering

Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo 16.04.2015

Thesis supervisor:

Prof. Matti Lehtonen

Thesis Advisor:

M.Sc. (Tech.) Claudio Donghi

Abstract

AALTO UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING

ABSTRACT OF THE
MASTER'S THESIS

Author: Semen Uimonen

Title: Energy Consumption of Escalators

Date: 16.04.2015

Language: English

Number of pages: 72

Department of Electrical Engineering and Automation

Professorship: Power Systems and High Voltage Engineering

Code: S-18

Supervisor: Prof. Matti Lehtonen

Advisor: M.Sc. (Tech.) Claudio Donghi

This thesis studies the impact of passenger load and different load scenarios on the energy consumption of escalators. The scope of thesis is analysis of energy used, in kWh, by an escalator pair with specific technical requirements, and effect of the passenger flow on energy consumption of the selected escalator pair. Previous studies revealed lack of knowledge about the effects of power saving modes on the power consumption profiles of escalators. This study provides typical daily energy consumption and people flow patterns for the escalator pair in an average store in the shopping center located in Helsinki, Finland. Additional data about escalator load impact and effects energy saving modes on electrical energy consumption and comparison of consumed electrical energy of escalator pair and the whole store is presented. Results of this thesis showed that in situations with relatively low traffic flow, particularly in department store environment, the main factor that affects energy consumption is the frequency of traffic flow. Results encourage continuing further long-term measurements of both electricity consumption and people flow patterns of intermittent escalators in situations with a different people flow frequency for further model development.

Keywords: Escalator, Energy consumption, Measuring, Traffic profile, Loading profile, People flow, Intermittent escalators

Preface

This thesis was inspired by the Energizing Urban Ecosystems (EUE) Program and is the second in the series. The work was prepared in Aalto University in collaboration with Tukia Consulting and under guidance of KONE Corporation.

I am very grateful to KONE for providing an opportunity to participate in the project. I would like to thank in particular my advisor Mr. Claudio Donghi for organization of meetings and supervision of work on this project. I wish to send special recognition to Mr. Dirk Lange for his assistance in technical matters regarding escalator technology and for the overall guidance of the research. I would like to acknowledge the following KONE employees: Mr. Harri Hakala, Dr. Marja-Liisa Siikonen, Mr. Hannu Nousu for organization and providing essential information to the content of the thesis. My sincerest appreciation goes to Mr. Kenneth Kronkvist and Mr. Raymond Ogienoyevbede for providing people flow measurement system.

I would like to thank Takowa Oy and Mr. Christer Lindstrom for cooperation in testing and selecting the measuring equipment for power flow measurements.

I wish to thank Aalto University and the entire Department of Electrical Engineering and Automation and in particular: Mr. Jussi Kuutti for providing data and background information on previous research studies conducted in the university regarding escalators; Mr. Ari Haavisto for arranging possibilities for equipment testing in the university and providing laboratory equipment; Mr. Tuomo Malkamäki for assistance with coding and tuning the sensors; my office mates Amjad and Jarkko for support and great office atmosphere; co-workers Asad and Mr. John Millar for open conversations during a cup of tea and overall support; my friend Ignacio for the greatest support and for being there for me when it was needed the most; I am endlessly grateful to my supervisor Professor Matti Lehtonen for providing an opportunity to participate in the project and for all the support and supervision along the way.

My deepest gratitude goes to Mr. Toni Tukia for enormous support and guidance on every step of the thesis. Working in a team made the project even more captivating and hopefully our collaboration goes above and beyond this particular work.

I want to thank my family and friends for their great support and help throughout the thesis.

Otaniemi 7.03.2014

Semen Uimonen

Table of contents

Abstract	2
Preface	3
Table of contents	4
List of figures	6
List of tables	8
Symbols and abbreviations	9
1. Introduction	11
1.1 Target of study	11
1.2 Scope of study	11
1.3 Structure of the thesis	12
2. Background	13
2.1 Escalator technology	13
2.2 Energy consumption of escalators	14
2.2.1 Fixed energy consumption	15
2.2.2 Variable energy consumption	17
2.3 Available energy saving technologies	18
2.3.1 Maintenance-free step chain	18
2.3.2 Regenerative solutions/devices	18
2.3.3 Eco-efficient operation	19
2.3.4 LED lighting	20
2.4 Available passenger detection technologies	20
2.4.1 Infra-red light barriers	20
2.4.2 2D video counters	21
2.4.3 3D stereo cameras	22
2.4.4 Pressure-sensitive mats	23
2.5 ISO 25745-1 Standard	23
2.6 Previous studies on escalators	27
2.7 Walking on escalators	30
2.7.1 The effect of passengers on an escalator	30
2.7.2 Walking factor	31
2.7.3 Walking speeds on escalators	31
3. Materials and methods	33
3.1 Measuring technology	33
3.1.1 Reference measurements	33
3.1.2 Long-term measurements	34

3.1.3 Means for people counting.....	35
3.1.4 Challenges in measurements of energy consumption of escalators	36
3.2 Measurement site.....	37
3.2.1 Configuration of the selected escalators	37
3.3 Evaluation of the passenger speed.....	39
4. Results.....	40
4.1 Reference power measurements.....	40
4.2 Long-term measurements	41
4.2.1 Reliability analysis of long-term consumption data	42
4.2.2 Consumption over longer period	44
4.2.3 Energy and power profiles	44
4.2.4 The impact of power saving modes.....	54
4.3 The impact of passenger load	55
4.4 Walking passengers - The effect on the energy consumption.....	57
4.5 Acceleration and deceleration - Effects on the power consumption	59
4.6 Electric energy consumption and energy saving effect	60
4.6.1 Electric energy consumption of an escalator pair	60
4.6.2 Energy saving effect	61
4.7 Estimation of fixed losses on different escalator types.....	62
5. Discussion	65
6. Conclusions	67
References	69
Appendix A	72

List of figures

Figure 1: Main features of an escalator [7].	13
Figure 2: Several states of operating of the escalator [8].	14
Figure 3: Relationship between passengers transported and the power drawn, adapted from Al Sharif, 2011 [9].	15
Figure 4: Infra-red light barriers system [16].	21
Figure 5: Tracking of objects with 2D video camera [18].	22
Figure 6: Infra-red vision of people tracking sensor, and view of the sensor [19].	22
Figure 7: Illustration of measuring instrument coupling points – escalators and moving walks [22].	25
Figure 8: Division of installed escalators in EU.	27
Figure 9: Time spent in each operating mode for commercial escalators with VSD.	28
Figure 10: Time spent in each operating mode for public transportation escalators.	29
Figure 11: Current consumed during the walking test at Moorgate [9].	30
Figure 12: Fluke 1760 circuit diagram for an escalator [29].	33
Figure 13: Diagram of the structure of the measuring system, made with EMU Allrounders and M-Bus logger, adopted from [30].	34
Figure 14: Design of the measured escalator, created with [33].	38
Figure 15: Principle of speed calculation.	39
Figure 16: Fluke power breakdown picture for upwards running escalator.	41
Figure 17: Fluke power breakdown picture for downwards running escalator.	41
Figure 18: Error compensation factor.	42
Figure 19: Error compensation for energy measurements in upwards running escalator.	43
Figure 20: Error compensation for energy measurements in downwards running escalator.	43
Figure 21: Usage and energy consumption division by escalators.	44
Figure 22: Average power on weekdays for upwards running escalator.	45
Figure 23: Average power on weekdays for downwards running escalator.	45
Figure 24: Average power on Saturdays for upwards running escalator.	45
Figure 25: Average power on Saturdays for downwards running escalator.	46
Figure 26: Average power on Sundays for upwards running escalator.	46
Figure 27: Average power on Sundays for downwards running escalator.	46
Figure 28: People flow on both escalators during weekdays.	47
Figure 29: People flow on both escalators during Saturdays.	47
Figure 30: People flow on both escalators during Sundays.	48
Figure 31: Average power and passenger data in 5-min averages for upwards running escalator on Friday 28.11.2014.	49
Figure 32: Average power and passenger data in 5-min averages for upwards running escalator on Saturday 29.11.2014.	49
Figure 33: Average power and passenger data in 5-min averages for upwards running escalator on Sunday 30.11.2014.	50
Figure 34: Average power and passenger data in 5-min averages for downwards running escalator on Friday 28.11.2014.	51
Figure 35: Average power and passenger data in 5-min averages for downwards running escalator on Saturday 29.11.2014.	51
Figure 36: Average power and passenger data in 5-min averages for downwards running escalator on Sunday 30.11.2014.	52
Figure 37: Power trace and passenger trace from [10].	52
Figure 38: Power vs time between consecutive passengers on upwards running escalator.	54

Figure 39: Scatter plot of power vs mass relation on upwards running escalator.	55
Figure 40: Scatter plot of energy vs mass relation on upwards running escalator. Standing.	55
Figure 41: Scatter plot of power vs mass relation on downwards running escalator. Standing. .	56
Figure 42: Scatter plot of energy vs mass relation on downwards running escalator. Standing.	56
Figure 43: Effect of walking.....	57
Figure 44: Comparison of electricity consumption of the escalator pair to the store.	60
Figure 45: Electricity consumption of each escalator.....	61
Figure 46: Comparison of electricity consumption with and without power saving modes on upwards running escalator.	61
Figure 47: Comparison of electricity consumption with and without power saving modes on downwards running escalators.....	62
Figure 48: Scatter diagram of power vs passenger data for Valmet escalator.	63
Figure 49: Scatter diagram of power vs passenger data for Kone escalator, equipped with energy saving modes.....	63

List of tables

Table 1: Time spent in each operating mode, adopted [18].....28

Table 2: Average walking speeds on stairs, from [19], [20]31

Table 3: Energy consumption of escalator during different modes, no load.....40

Table 4: Savings per day due to passenger walking.58

Table 5: Effect of acceleration and deceleration peak consumption.59

Table 6: Load impact for upwards escalator.....72

Table 7: Load impact for downwards escalator72

Symbols and abbreviations

Symbols:

$C_1, C_2, C_3, C_4, C_5, C_6$ – Coefficients depending on the mechanical design

E_f – Fixed energy consumption

E_t – Total energy consumption

E_v – Variable energy consumption

$E_{v/day}$ – Total variable energy consumption in kWh consumed per day

g – Acceleration due to gravity ($9,81 \text{ m/s}^2$)

h_d – Running hours of escalator

k_{wf} – Walking factor

m – Average mass of a passenger in kg

N – Average number of people per day

p_{day} – Number of passengers per day

r_e – Vertical rise

t – Time taken to reach the end destination

t_{max} – Time that passengers would spend on the escalator in seconds if none of the passengers walked

t_{walk} – Time passengers spend on the escalator in seconds when some of them elect to walk

v_e – Speed of an escalator

v_p – Speed of a passenger

Abbreviations:

CCTV – Closed Circuit Television

CT – Current transformer

DDNS – Dynamic Domain Name System

E4 – Energy Efficient Elevators & Escalators

ECT – European Central Time

ELA – European Lifts Association

EU – European Union

GHG- Green House Gas

LED - Light-emitting diode

PE – Protective Earth

PFU – Power Feedback Unit

SDK – Software Developer Kit

SML – Smart Message Language

VSD – Variable Speed Drive

VVC – Variable Voltage Constant Speed Drive

1. Introduction

By means of energy savings, improvements in energy efficiency are promoted as a way to increase productivity and sustainability of society. Significant impacts of energy savings can become a driving factor for economic growth and development. Outcomes and effects of energy saving technologies can be seen on several levels of economy [1]: at the international, national, sectoral and even individual levels. Among largest impacts of introduction of energy efficient technologies is the reduction of Green House Gas (GHG) emissions. Energy efficiency measures are used in many cases as the core cost-effective way to reduce GHG emissions.

Among largest projects that are aimed to apply energy efficient technologies is the European Union Climate and Energy 20/20/20 package. One of the main objectives is the reduction of GHG emissions by 20% from 1990 levels by year 2020, which is achieved by increasing the share of renewable resources and an improvement in the EU energy efficiency by 20 per cent [2]. In order to achieve these targets, improvements should be made on all levels, starting from smallest appliances.

According to [3], every year around 5000 new escalators and moving walks are being installed. In the past, escalators and elevators received relatively little attention from energy efficiency perspective. According to [4], improving existing technology could lead to reduction of energy usage by 28 per cent and reduction of GHG emissions by 100 000 tons per year. Improving our understanding of escalator technology helps us overcome the main barriers to energy efficiency. Lack of monitoring of energy consumption and lack of awareness about energy efficiency are ones of the major barriers [5].

1.1 Target of study

The target of the thesis was to understand the impact of passenger load and different load scenarios on the energy consumption of escalators.

1.2 Scope of study

The aim of this study was to analyze and study the energy usage of escalators with specific technical requirements in commercial buildings in different scenarios. During the period of study, it was possible to take measurements only from one site, a department store in a shopping mall located in Helsinki central area, Finland. This thesis does not view in detail the construction of escalators.

1.3 Structure of the thesis

The rest of the thesis is structured the following way: Chapter 2 introduces the background about escalators and energy saving technologies, available passenger detection technologies and analysis of results of previous measurements conducted by other parties. Chapter 3 describes methods and equipment used during measurements process, their characteristics and description of the measurement site and the specimen. Chapter 4 presents results of the measurement campaign and estimations of energy saving effects. Chapter 5 provides analysis of results obtained in Chapter 4. Chapter 6 draws conclusions obtained during this study and provide recommendations for further studies of the current topic.

2. Background

This chapter includes an overview of the technical knowledge of existing escalator technology, energy consumption, energy saving modes and people counting techniques. Information on the existing standard about current escalator measurements and overview of the previous research papers is also presented here.

2.1 Escalator technology

Escalators, alongside elevators, are the crucial elements that make it easy and comfortable to live and work in an environment that has a structure of several floors above and below ground. Usually, escalators are involved in about 3 to 8% of the overall electricity consumption of a building [5]. According to ELA statistics and ELA expert input survey results [5], there are approximately 75 000 escalators and moving walkway units installed in EU-27, where 80% are located in commercial buildings and 20% are in public transportation facilities (train stations, airports, etc.)

An escalator is a moving staircase for transporting people between floors of a building. It is generally agreed that an escalator is the most efficient means to move large numbers of people between floors [6]. The following Figure 1 shows the typical design of an escalator.

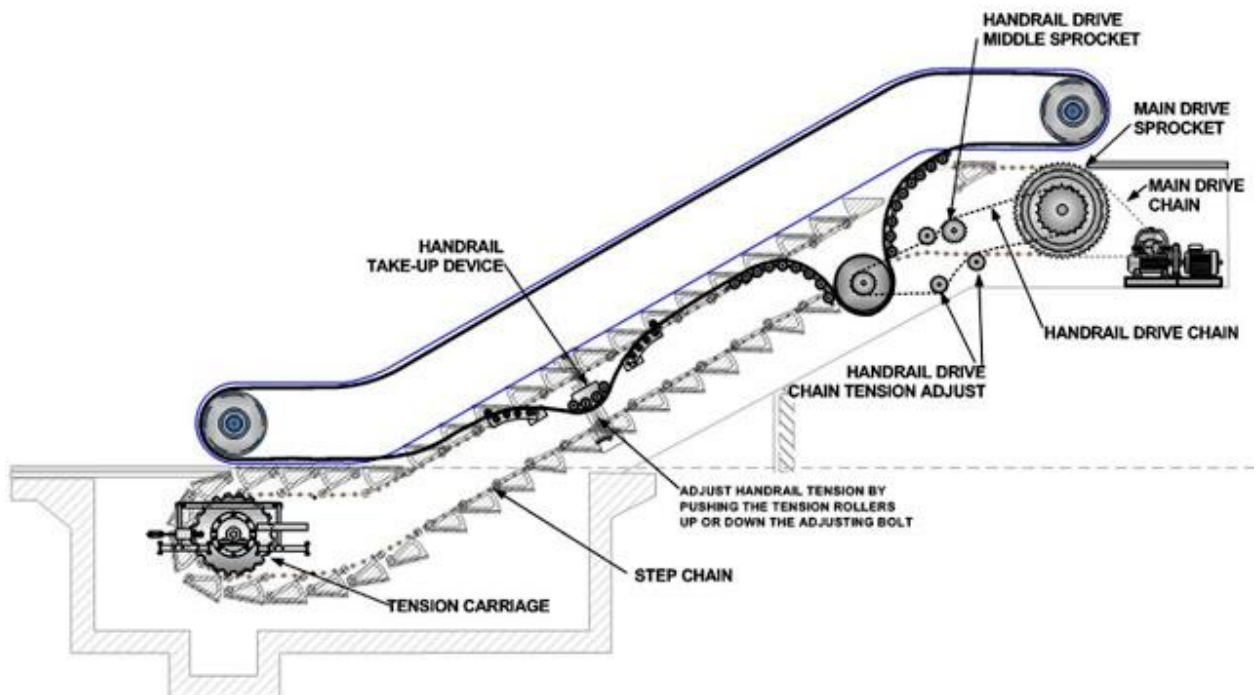


Figure 1: Main features of an escalator [7].

Figure 2 shows several states of operation of a typical escalator. Peak consumption period corresponds to the starting of the motor drive and overcoming static friction in stop-mode. Acceleration can be done in multiple ways, for example using

advanced technology for smooth acceleration which also helps to minimize the power consumption during this time. After some time without passengers boarding, escalator reduces its speed from normal speed, switching into low-speed mode. Consumption in this mode is usually close to half of the consumption during the normal operating mode. After certain amount of time escalator switches to stop mode, where electricity consumption is at its lowest. Although, it is not completely switched off, as auxiliary systems, such as lighting and control systems, are still working.

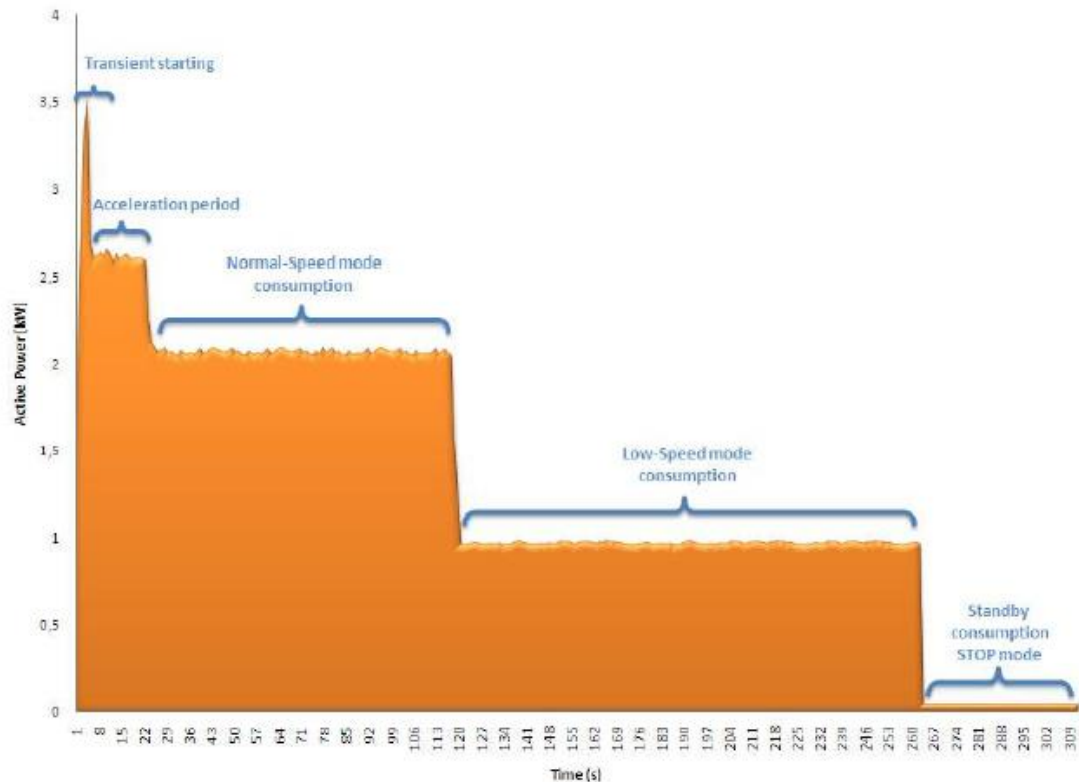


Figure 2: Several states of operating of the escalator [8].

2.2 Energy consumption of escalators

According to Al-Sharif [9] [10], the total energy consumption of an escalator can be divided into two groups: fixed losses and variable losses. In this thesis, it is called fixed and variable power consumption. Figure 3 illustrates relationship.

The energy consumption of the escalator depends on the following factors:

- Electrical and mechanical design
- Control and operation means: Y/Delta control, operational speed etc.
- Characteristics of passengers: daily amount of passengers, flow pattern and behavior
- Quality of maintenance

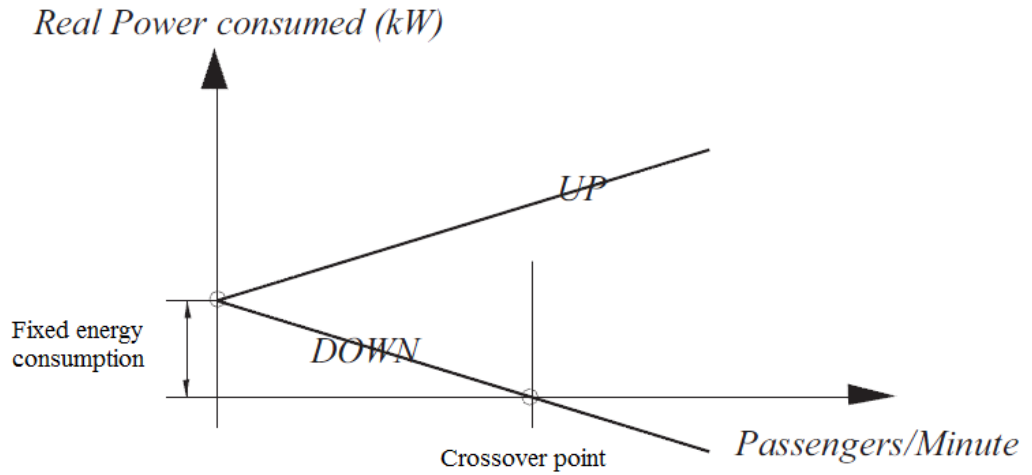


Figure 3: Relationship between passengers transported and the power drawn, adapted from Al Sharif, 2011 [9].

It can be seen from the figure above that fixed energy consumption is constant. Total energy consumption of the escalator will be:

$$E_t = E_f \pm E_v; (1)$$

Where E_f – fixed energy consumption, E_v – variable energy consumption, both in kWh

The sign of plus or minus depends on the escalator type: on downward moving escalator, the variable energy consumption decreases the total energy consumed with more masses travelling on the escalator until it comes to a crossover point where escalator starts to feed the power back to the grid [9] or to the brake resistors, depending on the used technology. On the upwards moving escalator, the variable energy consumption, on the contrary, increases total energy consumption of the escalator. More information about fixed and variable energy consumption is presented below and mass dependency, or load impact, is discussed in Section 4.3.

2.2.1 Fixed energy consumption

Fixed energy consumption is equal to the power drawn by the escalator when no passengers are travelling on the escalator. This consumption is influenced by the efficiency of motor and efficiency of the gear [9].

It is necessary for the escalator to overcome friction in the handrail, which was revealed from practice to have the most impact to the fixed power consumption, and step-band, as well as inefficiencies in the motor and gearbox, when it is starting or running unloaded. These energy losses are mainly dissipated as heat in the following parts of the system [10]:

- Drive chain, step chain, bearings
- Gearbox
- Low speed bearings on shafts
- Handrail and guidance systems

Paper [10] covered the effects of mechanical design on fixed power losses. The three main criteria for it are:

1. Type of bearings used in the wheels and step chain
2. Type of guidance system for step band and step chain
3. Type of gearbox

Different types of systems were compared together and plotted against vertical rise. Findings show that fixed losses for each design vary drastically, the biggest being due to type of step chain and bearings.

Two methods covered estimation of fixed energy consumption [9]:

- Method A

The most straightforward method to calculate fixed energy consumption is based on assumption that the escalator for the last 30 minutes of its operation in the day is rather lightly loaded and only few passengers use it. This can be seen in results section in figures from Section 4.2.2. Conceivably, the average of the power drawn for these last 30 minutes is a satisfactory representation of the fixed power consumption with a relatively small error. Certainly, errors arise from the number of passengers who might use the escalator in this short period of time. Most likely this method is not the best option for estimation of fixed power consumption of escalators in the department stores on weekends due to the fact that those stores close earlier and people tend to present there until the last minute [9].

It is not very reasonable to use the data of the first 30 minutes of the escalator running time. It is not going to be a representative picture for the whole day because during the first hour of performance the escalator is still warming up. Same principles apply to both upwards and downwards escalators. It is so that the downward escalator represents the maximum of its power consumption, while the upwards, on the contrary- the minimum [9]. Simplicity of this method and the fact that only 30 minutes of power measurements are required speaks in favor of the method, but it has some accuracy issues and hence, should not be used under certain circumstances.

- Method B

This method utilizes both power and passenger data. It is a more accurate method for deriving fixed energy consumption of an escalator, because any usage of the escalator by passengers is taken into account. In this method, all the data is plotted

on a scatter diagram (power data vs passenger data). The best fitting trend line represents the relationship between passengers and power and its equation. As it was mentioned earlier, the fixed power consumption of energy is the consumption when no passengers are on board the escalator. For this reason, to get the fixed energy power consumption it is necessary to solve the equation when number of passengers equals to 0 [9]. Result of application of this method is presented in the Section 4.7.

As a result, equation for estimated fixed energy consumption for continuously running escalator looks the following way [10]:

$$E_f = (C_1 * r_e + C_2)h_d \quad (2)$$

Where, C_1 and C_2 are coefficients depending on the mechanical design, r_e -the vertical rise and h_d - is the running hours of escalator.

2.2.2 Variable energy consumption

Variable energy consumption depends on the number of daily passengers, their average mass and the rise of the escalator. In paper [10], variable energy consumption was calculated by measuring total energy consumption and subtracting fixed energy consumption from it. However, it turned out that the values were only 70% of theoretical. For this reason, a “walking factor”, which is explained in more detail in Section 2.7, was introduced. Passengers walking up spend less time on the escalator, and, therefore, escalator consumes less energy for taking them on top and returns less energy if they are walking down on the downwards moving escalator.

The following formula represents the approach stated in the paper [9] on calculating variable energy consumption:

$$E_{v/day} = \frac{p_{day} * g * r_e * m * k_{wf}}{3600000}; \quad (3)$$

Where: $E_{v/day}$ – total variable energy consumption in kWh consumed per day

p_{day} – number of passengers per day

r_e – vertical rise in m

g – acceleration due to gravity ($9,81 \text{ m/s}^2$)

m – average mass of a passenger in kg

k_{wf} – walking factor.

2.3 Available energy saving technologies

Eco-efficiency has been proposed as one of the main tools to promote a transformation from unsustainable development to sustainable [11]. It is based on the concept of creating more goods and/or services while using fewer resources and creating less waste and pollution. The eco-efficiency of an escalator can be improved by utilizing eco-efficient technologies and by operating the escalator in a more efficient way. Among the most broadly used technologies is the Variable Speed Drive (VSD). There are also other solutions, such as Variable Voltage Constant Speed Drive (VVC). It uses a VVC controller to reduce the energy by controlling the motor voltage and improving motor power factor only at times when fewer people are using the escalator, but the speed is kept constant [12].

In [13], four ways are proposed to make an escalator eco-efficient:

1. Maintenance-free step chain
2. Regenerative solutions
3. Eco-efficient operation
4. LED lighting

In addition, almost each of these solutions also provide carbon footprint reduction, which is defined as the total sets of greenhouse gas emissions caused by an organization, event, product or person [14].

The following sections expose more information about each of these solutions:

2.3.1 Maintenance-free step chain

With development of permanently greased and sealed chain links, it is no more required to use extra oil for chain lubrication. Sealed links are used within this technology to comprise a permanent lubrication. These sealed links or capsules provide protection from dust and dirt penetration inside the links. The outcome is a reduced wear-off of chain links and bushings in the chain. No oil consumption enables average oil savings with commercial escalators up to 1-2 liters per month and about 5 liters per month in infrastructure escalators [13].

2.3.2 Regenerative solutions/devices

These features are necessary to be able to feed generated energy back to the network when combined with inverter technology. Installation of such an inverter with a power feedback unit (PFU) into existing escalator technology allows regenerating power from the downwards running of the passengers when the escalator is loaded over a certain amount, which is the cross over point on Figure 3 in Section 2.2. However, the disadvantage of this solution is the special need for effective filtering of electromagnetic emissions with related material cost. Additionally, the broadly used in escalators,

asynchronous squirrel cage induction motors provide the capability to feedback generated energy without any means of PFU and regenerative devices [13].

This technology is contributing towards efficiency only when there is an extensive use of the escalators, such as those installed on metro stations with a very dense passenger flow. In addition, this solution replaces brake resistors that consequentially regenerate heat. It means that additional fan cooling system can be removed [13].

2.3.3 Eco-efficient operation

One of the easiest and effective solutions is to stop the machine when its operation is not required. There are a number of methods to reduce the energy consumption of an escalator during its operation [13].

1. Stop & Go operation

This is the mode when escalator stops running when it is not in use. There is almost no power consumption when escalator is stopped. This mode is recommended for low traffic or for such a passenger flow which has long intervals of no passengers. Its energy saving capability can reach up to 50% depending on the passenger traffic, load, motor and drive. This mode is compatible with other technologies, such as star/delta energy saving [13].

2. Star/Delta energy saving

This is a conventional energy saving feature as a basic option. In low traffic the motor is switched into Star-operation mode, increasing the efficiency of the motor when no or few passengers are using the escalator. On the other hand, when there are much more passengers boarding the escalator the motor switches to Delta-operation mode for optimal use. This mode is suitable most for low load situations and is capable of providing up to 25% energy savings, depending on passenger load, motor and drive [13].

3. Stand-by speed (by inverter control)

This technology allows the escalator to run at reduced speed with no passengers on the step band. For example, escalators that are installed in the stores, just like ours, that changes its speed from 0,5 m/s to a stand-by speed of 0,2 m/s. It is recommended to install this technology into escalators with medium traffic or with several peak and non-peak intervals. It can also be combined with Stop & Go technology, which provides additional energy savings. Depending on the traffic, load, motor and drive, savings can reach up to 40% [13].

4. Traffic dependent operation (2-Direction-Mode)

With this mode, escalator is able to run automatically in the direction from where the first passenger is approaching. The escalator stops completely when there are no passengers and it is not in use. This technology is recommended for places where

there are low traffic conditions and long intervals between passengers. Since this solution enables automatic operation in both directions, the installation of a second escalator is not necessary [13].

2.3.4 LED lighting

In comparison to old fluorescent tube lighting with 60 W/m of installed appliances, LED lighting technology consumes only 2-10 W/m. In addition, it has extended life service up to 50 000 hours and energy savings can reach up to 80% in comparison to conventional lights [13].

2.4 Available passenger detection technologies

Information about passenger flow and detection of passengers when they enter escalator is of great importance for several reasons:

First of all, it is necessary to detect the approaching passenger beforehand in order to increase the speed of the escalator prior to the moment he steps on the step band. This is also a safety reason. Besides, people flow information is essential for optimization of the escalator performance and configuration of its saving modes. It can help to pick accurately the interval times between nominal and crawling speed and auto-off time. Possibility of optimization is discussed in Chapter 5.

There are numerous available solutions for both detection and passenger counting from a number of different suppliers. However, many of them are not capable of providing a detailed enough analysis of the people flow situations or are not meant specifically for escalator counting needs, which exposes some additional difficulties for tuning those devices in the proper way.

2.4.1 Infra-red light barriers

An infra-red light barrier is a technology that is widely used and is a low cost people detection system. It consists of a transmitter (the source of the infra-red beam), infra-red detector and a reflector. Usually both transmitter and detector are located on the same side, while reflector is on the opposite side of the entrance gates. Each time a passenger steps in the path of the infra-red beam, between reflector and transmitter, the beam is interrupted and the escalator switches on. When infra-red beam path connection is not interrupted for a certain amount of time, the escalator switches off for energy saving [15]. Figure 4 shows the installation of the infra-red beam system in the escalator gate.



Figure 4: Infra-red light barriers system [16].

The main purpose is to detect people, but its installation can also be used for people counting. Likewise, they provide a number of problems which affect accuracy of these sensors. Similar sensors were used in a paper work, conducted in Aalto University in 2011 [17]. Slight difference was that a pulse from infra-red sensor triggered the counting feature on the board across the gate. Duration of this pulse is 200 ms and a delay up to 100 ms after. These factors limited the ability to distinguish passengers that are walking close to each other. As a side-mounted device this sensor is not able to distinguish people walking in parallel. Therefore, it causes some undercounting, especially during busy metro station hours. The small delay between counting pulses also affects the measurement data. Since it is a beam sensor, the height should be chosen carefully in order not to cause undercounting due to some people of smaller height, like children. It is also important not to put it too low, so that the waving hands during passenger's walking do not cause overcounting of the sensor.

2.4.2 2D video counters

These devices require cameras to be installed at sight. Integration is also possible with existing CCTV cameras, although they require specific arrangement. They can be installed overhead or with a different angle, depending on the needs. Live counting is done with processing the captured images via specific algorithms by the software. There is a range of ways to transfer data, including Ethernet and Wi-Fi [18].

Among advantages of 2D video counting systems is the ability to store video data footage that can be used later for verification processes if necessary. System enables remote access and surveillance of multiple areas is feasible. Principle of object tracking is presented in Figure 5.

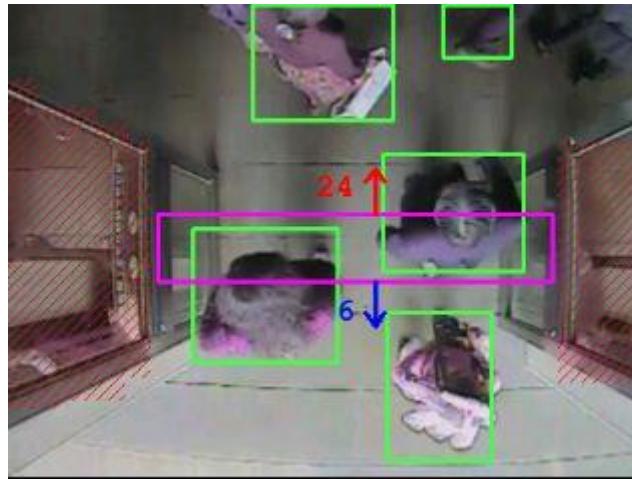


Figure 5: Tracking of objects with 2D video camera [18].

Naturally, these cameras are more expensive than simple infra-red sensors and require more storage capacities to contain the video footage.

2.4.3 3D stereo cameras

3D person tracking sensors are becoming more and more popular for various people counting needs. In many cases, companies or startups provide a full-pack solution for necessary people counting needs, claiming they have a state of art device and do not want to publicize algorithms or technology. These sensors use stereo vision algorithms. They are capable of tracking every individual person in the viewing area of the sensor. Most of them provide possibility to place counting lines and different type of zones where a tracking object can be evaluated directly on the sensor. A web interface can be used for configuration and live result/status monitoring without the need for installation of any server software [19]. Usually, these sensors can be integrated into existing software frameworks using the windows or linux SDK. These sensors are mounted overhead and are able to make height measurements. As these are the most complicated technology wise solution, they are also ones of the most expensive. Figure 6 shows the view of one of the similar sensors discussed above.

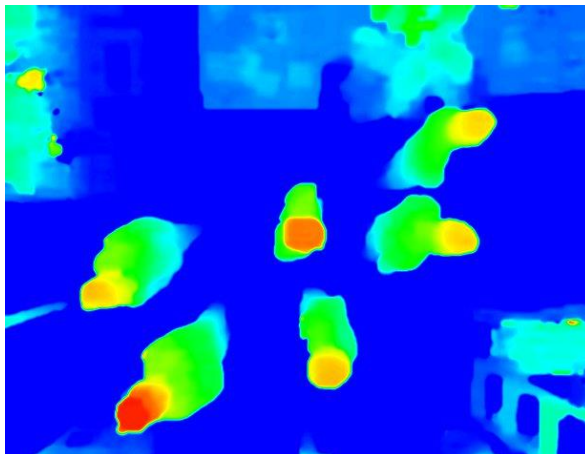


Figure 6: Infra-red vision of people tracking sensor, and view of the sensor [19].

Usually, these systems are not used by means of escalator control, for example for starting an escalator when a person is in the zone of the sensor. Although since these sensors provide a lot of freedom in terms of customization and it is possible to integrate them into software framework- it is also possible to integrate it with the escalator technology.

2.4.4 Pressure-sensitive mats

Pressure sensitive mats are a system commonly used in escalator technology which detects the weight of a passenger. However, this is not suitable for counting passengers, but it is a well-established technology for sending a signal to start the escalator.

There are two types of pressure-sensitive mats:

- There are two conductive steel plates which are held apart from each other by a thin layer of non-conductive material. When the mat is clear, there is no signal going through the circuit. As soon as it is stepped on, electric current runs through the conductive plates, as the non-conductive material is diminished under pressure. These mats are also often used as safety equipment [20].
- Another way is to use piezoelectric material. This is a kind of solid material, for example crystals or certain types of ceramics, that accumulate electrical charge in response to applied mechanical stress [21].

2.5 ISO 25745-1 Standard

This section provides some basic information about the ISO 25745-1 Standard [22]. The first part of the standard specifies methods of measuring actual energy consumption of lifts, escalators and moving walks on a single unit basis. In addition, it provides methods of carrying out periodic energy verification checks on lifts, escalators and moving walks in operation. Prescribed measurements method forms a foundation and framework for the upcoming standards for classifying devices by their energy efficiency. In accordance with ISO 25745-1 these power consumption verification measurements at Escalators shall not be carried out before a run-in time of 1.000 operating hours have been reached [22].

The standard suggests performing measurements for powers in standby condition, autostart condition, slow speed condition, no load condition and ancillary power. These terms have the following definitions, specified by the standard:

- *Standby condition* – for escalator or moving walk – condition when the escalator or moving walk is stationary and powered on and can be started by authorized personnel.
- *Autostart condition* – condition when an escalator or moving walk is stationary, powered up and ready to start when initiated by passenger detection.

- *Slow speed condition* – condition when an escalator or moving walk is running at slow speed without passengers.
- *No load condition* – condition when an escalator or moving walk is running at nominal speed without passengers.
- *Ancillary equipment* – equipment such as lighting, fans, heating, alarm devices and emergency battery supplies.

Figure 7 provides locations for necessary measurements given in the standard. For escalators and moving walks the no load condition is measured first. After first measurements, periodic checks of power in the no load condition may be performed at any time during the operating life [22]. This is done to determine changes in the energy consumption of the equipment. In the case of multiple escalator installations, each unit is supposed to be tested as a standalone piece of equipment.

According to the standard, the measuring instrumentation should be a power meter with: capabilities of measuring active power of at least three values per second and a sufficient measuring range for a possibility to measure recovered energy. The measured results should be of an accuracy of at least $\pm 10\%$. In our measurements these requirements were fulfilled.

The test set-up conditions include that public usage was prohibited during testing and no parameters were changed during the measurements. In order to get adequate results, it is necessary to also run the escalator prior to measurements until it reaches a stable machine temperature.

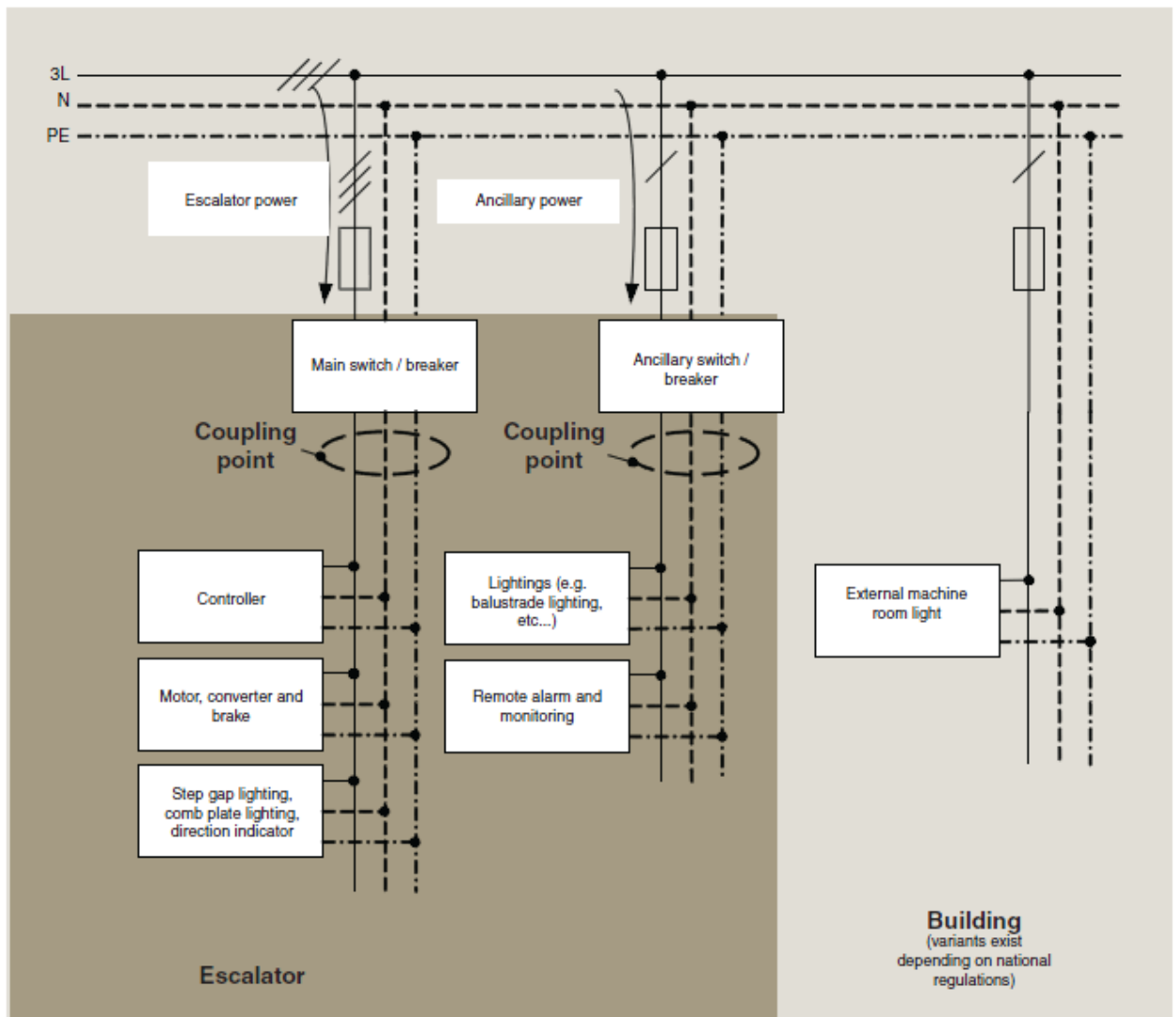


Figure 7: Illustration of measuring instrument coupling points – escalators and moving walks [22].

The power measurement procedure defined in the standard is the same for each required condition, except for the number of full revolutions in some cases, and is repeated. Goes as follows:

1. Main power measurements – running.
 - a. Connect the power meter to the main power lines at the main power coupling point.
 - b. Measure and record the active power in watts.
2. Power measured in the stand by condition.
3. Power measured in autostart condition (if available).
4. Power measure in slow speed condition (if available).

Procedure should be continued for at least one complete revolution of the step band.

5. Power measured in no load condition.

Procedure should be continued for at least three complete revolutions of the step band.

6. Power measured in ancillary equipment goes as follows:
 - a. Connect the power meter to the ancillary power lines at the ancillary coupling point, as per Figure 7.
 - b. Measure and record the active power.

2.6 Previous studies on escalators

Several studies have been conducted on the energy consumption of escalators. Most of the time reports about escalators are included into reports about elevators and take a smaller role there. Perhaps the most known monitoring campaign in Europe, called Energy-Efficient Elevators and Escalators (E4) Project [8], [23] was targeted at the improvement of the energy performance of lifts and escalators in the tertiary sector buildings and in the multi-family residential buildings. Among conclusions of this project was the statement that the reduction in standby energy consumptions is an opportunity that is worth taking into consideration. The measured values of standby consumption vary from around 14.3% to 23.4%. Standby consumption is considered to be the sum of the low-speed mode and the stop mode consumption [8]. According to European Lifts Association (ELA) statistics there are 75 000 escalators and moving walks installed in the EU-27. The following picture represents estimated division of the existing escalators in [23]:

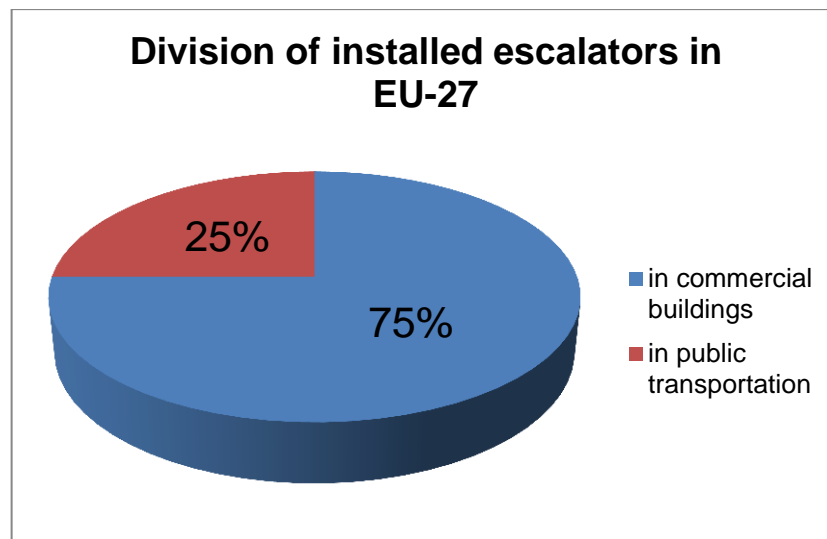


Figure 8: Division of installed escalators in EU.

It is mentioned that 30% of these are equipped with Variable Speed Drive (VSD). Based on ELA experts opinion it is considered that escalators in public transportation facilities consume around 75% more electrical energy.

The times spent in each operating mode assumed were summed up in the following table:

Table 1: Time spent in each operating mode, adopted from [23].

	without VSD		with VSD	
	commercial	public transportation	commercial	public transportation
Running, h	4368	7280	1872	2912
Slow speed, h	0	0	2496	4368
Stopped, h	4392	1480	4392	1480
Total	8760	8760	8760	8760

Time spent in each operating mode for commercial escalators with VSD, of total 8760 h

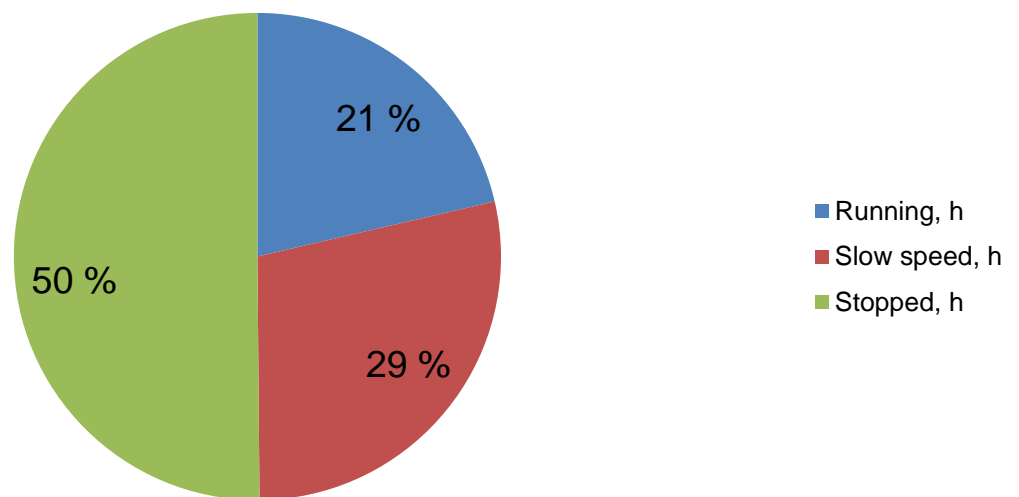


Figure 9: Time spent in each operating mode for commercial escalators with VSD.

Figures 9, 10 show an estimation of how much time escalators with VSD system spend in each of the operating modes. It can be easily seen why an escalator in the public transportation consumes much more electrical power than the one in a commercial building. Most of the time the commercial escalators are switched off and public transportation system works longer hours. Additionally, they spend more time in running mode, than those of commercial buildings.

Time spent in each operating mode for public transportation escalators with VSD, of total 8760 h

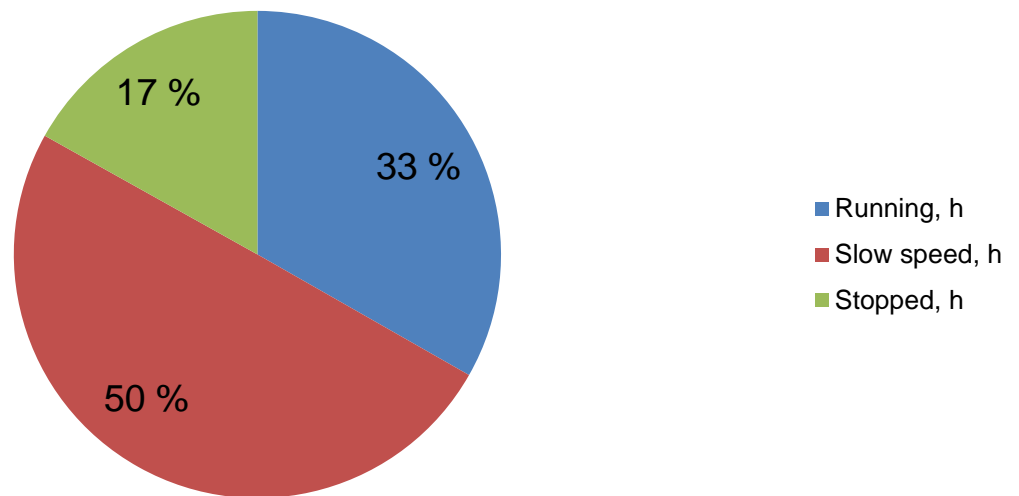


Figure 10: Time spent in each operating mode for public transportation escalators.

The discussed earlier reports [5] [8] used best available technologies for estimation of savings potentials in escalators and moving walks. A potential reduction in electricity consumption was estimated to be around 28%, which would also possibly lead to a reduction in carbon emissions of 100 000 ton per year [23].

Another paper was written in Aalto University [17], conducting a report about energy efficiency of two escalators of different age at subway stations in Helsinki area. Energy consumption measurements were taken together with people counting. Results showed remarkable differences between the escalators and pointed out that passenger counting together with power measurements can be exploited in energy efficiency comparison of different type of escalators.

2.7 Walking on escalators

In this part walking speeds on escalators, percentage of walking passengers and the walking factor and its impacts are presented. Calculations of additional electrical consumption or energy savings due to people walking are presented in section 4.4.

2.7.1 The effect of passengers on an escalator

A question that has been raised in several papers in the context of escalator energy consumption is whether passengers consume more or less energy when they walk up an upward moving escalator and what is the effect of walking down on the downwards moving escalator [9]. In his paper, Al-Sharif writes about a test that was conducted on a public escalator, where there were selected passengers that, at first, were standing on a moving escalator and then they were walking up. The power drawn was monitored by measuring currents. The results can be seen from the Figure 11 below:

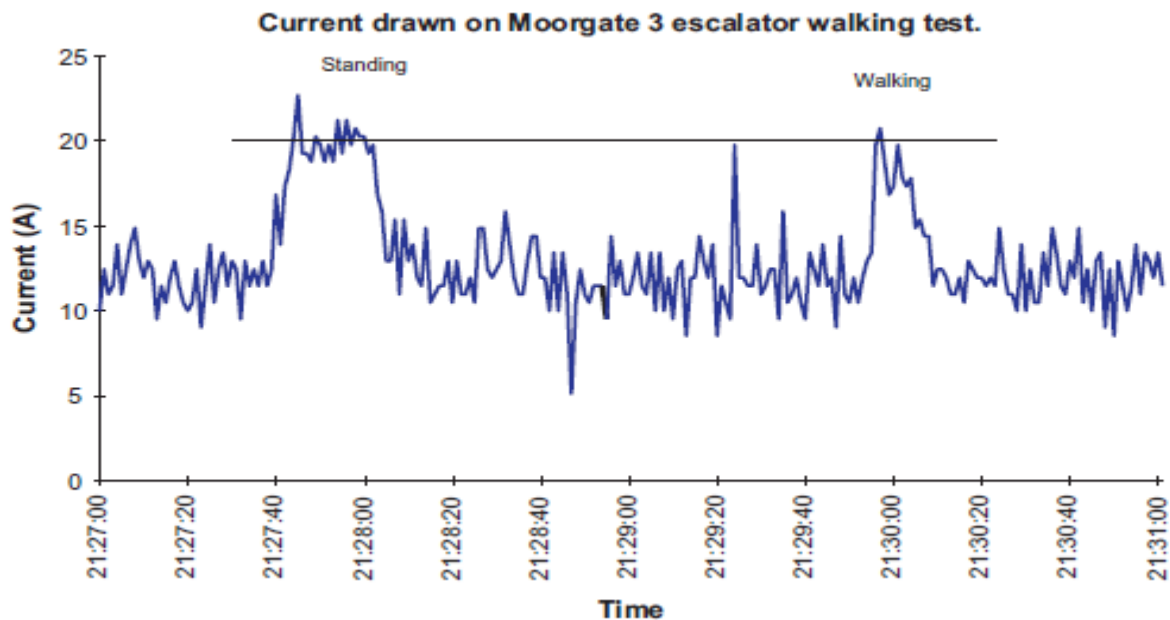


Figure 11: Current consumed during the walking test at Moorgate [9].

Peak of the power drawn in two cases is nearly the same and the fact that passenger spends less time when walking upwards shows that less energy is used on the upwards moving escalator.

One explanation of this is given by Al-Sharif in his work [10]. Passengers approaching an upward moving escalator accelerate themselves up to the running speed of the escalator in the direction of the inclination angle. The power required by the escalator is the one that is necessary to keep them moving in the direction of travel with the rated linear speed (0,5 m/s in our case). It is the same power in case of walking or standing, but during walking they spend less time on the escalator since their speed equals to the sum of the speed of escalator and their walking speed. The difference in energy is

supplied by human muscles. Regarding walking on downwards moving escalator-passengers return less energy to the power supply than stationary passengers. The power drawn from the system in the saving mode is far less than if the passengers are standing. It is illustrated further in Figures 16, 17. Note that this is the case for escalator where people flow is not so constant, and is not capable of big amounts of passengers to be able to produce electricity back to the grid.

While conducting our tests regarding power-mass relations, walking was also a part of the test, see Table 6 in the Appendix A. A comparison is presented in Figure 43 of Section 4.4.

2.7.2 Walking factor

In paper of Al-Sharif [9], a walking factor was introduced and discussed. It is defined in papers as the ratio between the time that passengers actually spend on the escalator and the time that they would spend if no walking took place.

$$k_{wf} = \frac{t_{walk}}{t_{max}}; (4)$$

Where k_{wf} is the walking factor (less than or equal to 1), t_{walk} is the time passengers spend on the escalator in seconds when some of them elect to walk, and t_{max} is the time that passengers would spend on the escalator in seconds if none of the passengers walked.

2.7.3 Walking speeds on escalators

The following table was adopted from [9], [24] and [25], showing walking speeds of passengers on stairs with different inclination angles:

Table 2: Average walking speeds on stairs, from [24], [25].

Angle of inclination, deg	down, m/s	up, m/s
32	0,67	0,51
27	0,77	0,57
35	0,62	0,57

If escalator is standing still it is considered by many people to be just a set of stairs, but in fact, escalator steps are usually of different height of and are not specifically designed for normal walking. In cases of walking risk of tripping and falling is increased.

Andrews and Boyes [26] calculated walking speeds of passengers on 30° escalators 0,63 m/s and 0,66 m/s for upwards and downwards escalators respectively. These measurements were carried out in London Underground at Victoria Station.

During our measurements the average speeds of all the passengers were found to be much smaller. Among reasons for these low average speeds is the fact that our escalator pair was installed in the store, where people do not rush the same way they do on the metro station or in places of public transportation systems, and the length of the escalator.

3. Materials and methods

This chapter defines methods and tools used for gathering the essential data for from measurement sites as well as the challenges that were faced during measurements. Information about the measured escalators is presented here. Meters and people counting devices are introduced in this chapter along with accuracy and methods of their installation.

3.1 Measuring technology

Suitable equipment was thoroughly selected for the measurements procedure. Energy consumption measurements were done in short- and long-term, where short-term measurements were used as a reference to longer ones. This was necessary to find error in readings of the long-term measurement equipment in order to improve accuracy.

3.1.1 Reference measurements

Fluke 1760, Three-Phase Power Quality Recorder was chosen for the power and energy measurements task. It is an accurate power quality monitor with fast sampling and recording rate (up to 5 times per second). It matches the accuracy requirements set by the ISO standard 25745-1 [22], being IEC 61000-4-30 [27] Class-A equipment.

Observations with Fluke were made for one hour for upwards escalator and one and a half for downwards escalator. It would provide the reference cycle energy consumption readings executed after the installation of the long-term measurements equipment. Fluke data was considered to be without error and could be used to determine the error in the long-term measurement devices. Process of error determination consists of comparison of readings stored by the Fluke and long-term measurement equipment that are installed to supply of the same escalator. The resulting comparison is presented in Section 4.1.1.

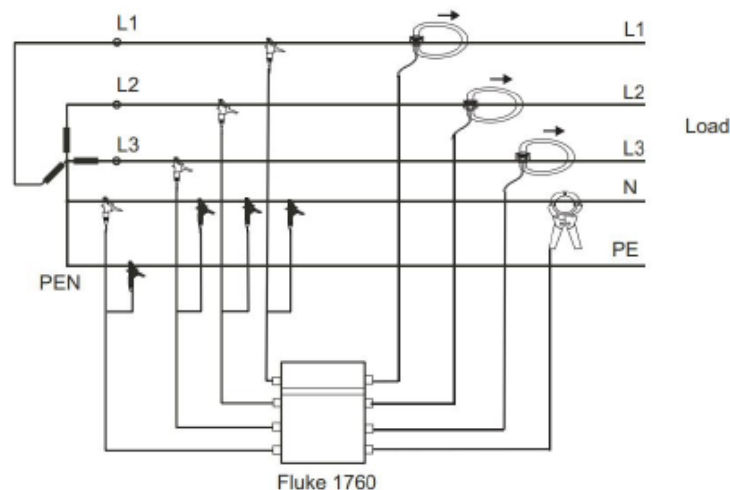


Figure 12: Fluke 1760 circuit diagram for an escalator [28].

Connection of the measurement device was made as per Figure 12 above. Measurement of currents in the neutral wire is optional and was not performed in this thesis.

3.1.2 Long-term measurements

The main focus of thesis work is on the long-term measurements. Required equipment was supposed to be reasonably accurate, cost-efficient and to have a convenient communication system with enough data storage capacity.

For these aims, equipment was chosen from the same company as in the project regarding elevator energy consumption from a year ago, in the frame of the same EUE project [29]. EMU Allrounder three-phase kWh meters were purchased. This line of devices from the manufacturer had a proven suitable behavior and accuracy. Accuracy was verified and suitable functionality set in university laboratory prior to installation. M-Bus version of the meters was chosen with an M-Bus data logger [30]. The basic principle of operation is presented in Figure 13. The M-Bus is using Ethernet cable for connection to the modem and a link between the logger and the server is established via a router with 3G capabilities. The M-Bus Logger sends the measurement data to the server using Smart Message Language (SML). It is possible to download reports and see statistics of the connected devices on the Smart-me.com server, which was provided as a service with purchase of the devices. In addition, more detailed and full data could be downloaded directly from the M-Bus logger through Dynamic Domain Name System (DDNS).

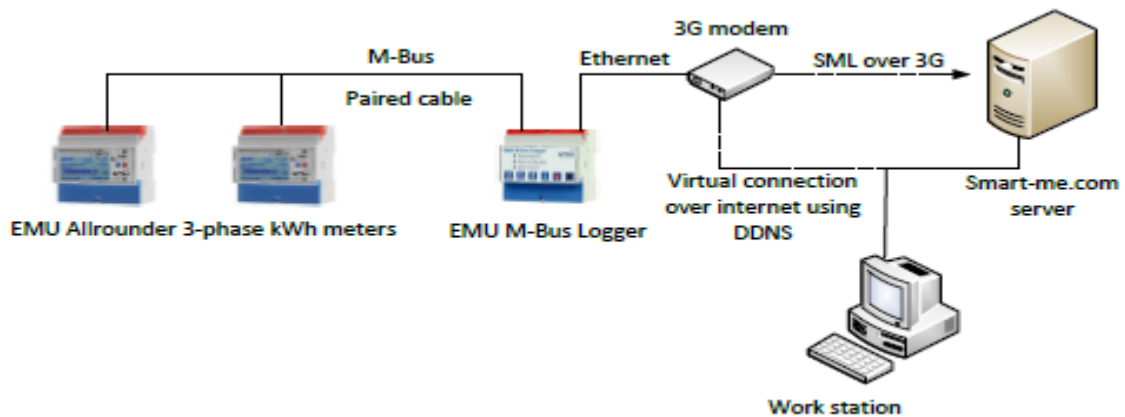


Figure 13: Diagram of the structure of the measuring system, made with EMU Allrounders and M-Bus logger, adopted from [29].

Current transformers (CT's) purchased for long term measurements are Celsa 60/1 A, 0,2 VA, Class 3, which means 3% error at nominal current. These are commonly used for protection and relays rather than measurements. However, those of Class 1 have a higher nominal rating on the primary side (100 instead of 60). It is a challenge to make accurate long term measurements of a nominal current smaller than 5% of nominal. Most accurate split-core CT's can reach Class 0.5, but typically these are for nominal currents of over 500 A [31].

Most of the error in our measurements is seemed to be induced by the current clamps: not only error in amplitude of current, but also due to an error in the phase angle. For better accuracy it might be useful to use solid-core window transformers, but these would have required temporary disconnection of existing wiring, which should have been avoided at the site. The issue had to be addressed and solved, which is described in Section 4.2.1.

3.1.3 Means for people counting

We were provided with 2 stereo camera sensors from KONE. One of the sensors was made for 2-4 m measurements and the other for 2-6 m measurements, which is the height from the sensor to the floor. These person tracking sensors use stereo vision algorithms to track every individual person in the viewing area of the sensor. There was a possibility to provide counting lines, which were used for speed estimation and people counting. A web interface was used for configuration and calibration, which also provided some live results and showed current status of the sensor. It is supposed to be mounted overhead. These sensors have a wide viewing angle of 105 degrees.

Unfortunately, the web interface of the sensors was not suitable for data storages. It showed only the total amount of people who created events, without detalization. These sensors are compatible with Windows SDK, therefore existing Java code was enhanced which made it possible to run the code application from external PC. It made it possible to track the detailed data of each event of each sensor (e.g. Object ID, Type of event, Time in UNIX, which was later used to calculate time difference and Timestamp in normal format (ECT). Additionally, it provided possibility to also store the whole log and separate data in the desired format for further assessment and correlation with the power measurements data.

Both of these devices are powered over Ethernet cable, and are compact and easy to install. Sensors were tested in the university before installation on the site and once again in the field before carrying on with data acquisition. Accuracy tests were verified with manual counting and their results were satisfactory: showing 93,47% accuracy.

Due to existence of an inclination angle of 35°, and several other obstacles, the sensor was installed in the same plain as the escalator floor. We were also afraid that since sensor picks objects in the stream from the preset height, the fact that people are moving up or down would affect the data detection and same person would get different object id's, while crossing our projected lines. This would prevent us from obtaining the speed of passengers' data.

While acquiring the data, we noticed that mistakes came mostly from:

- times when the sensor could not accurately distinguish the amount of people in the group when they were bunched up together
- times when a tall person was screening a smaller one – in this way it usually was noticed by the sensor on the first line, but missed on the second
- times when people were leaning towards the wall on the downward escalator, probably because the wall had to be masked.

The sensor was placed directly over the entrance of the upwards escalator, therefore the downward escalator view had a small additional angle.

It was necessary to calibrate the sensor while the floor was moving. In this way it made far less mistakes in people counting than in the situation when it was calibrated with static floor.

3.1.4 Challenges in measurements of energy consumption of escalators

One of the challenges for long-term measurements was the fact that the current of the escalator is low and this was not a suitable value for current transformers. It is said that they give accurate values for measurements in the range of 5-95% of the nominal value, where in our situation it has rarely exceeded 6A. Current clamps had to be used instead of braking into the circuit or connecting straight through the long-term measurement device because we were not allowed to disrupt the existing circuit.

Since short-term measurements could not have been done while there are passengers boarding escalator, they had to be done early in the morning before the store officially opens. As it was noted in the standard ISO 25745-1 [22] and in [9] an escalator had to be properly warmed up before measurements could take place. The actual warming up time, beyond which it is safe to say that the motor is warmed up, was not indicated in the sources. According to KONE measurement specification, a run-in period of 20 minutes is considered to be acceptable for measurements to be carried out.

Among other challenges regarding power measurements was the situation, where each of our measurement devices: long-term measurement devices, short-term measurement devices for reference and people counting devices had different timestamps while conducting measurements. It required additional effort to perform synchronization of the data, especially the short-term measurements. Since they were done for a shorter amount of time and the resolution of those measurements is much higher, it was not trivial to find the exact time difference in the timestamp.

In Section 2.6, a previous study was mentioned, where two escalators were compared with each other. Attempting to compare energy consumption of both escalators with the methods described in [9] and Section 2.2.1 it turned out that they are not totally applicable to the situation of the escalators that are equipped with power

saving modes, such as slow-speed mode, for example. A more detailed result is presented in Section 4.6.

3.2 Measurement site

The time period and model specification of the desired escalator allowed making measurements in a shopping mall in Helsinki area. The escalator pair is located in a two-floor department store, leading the passenger flow between first (400 m²) and second floor (1000 m²), occupied by personnel and customers. It was a challenge to find the desired specific model of the escalator in Finland.

3.2.1 Configuration of the selected escalators

Specification required:

- commercial environment: department stores, malls, shopping centers
- model: "*KONE TravelMaster™ 110* (TM 110)"
- vertical rise: 4,5 m
- inclination angle: 35°
- step width: 1000 mm
- speed: 0,5 m/s

Typical configuration of the escalator is:

- Motor: Squirrel cage asynchronous motor 7,5 kW
- Gear: Worm gear
- Starter type: inverter
- Slow speed or stopping when no passengers on the step band and stop mode when there are no passengers for 3 minutes

Dimensions and detailed design of the measured escalator is presented in the Figure 14, created with an escalator designer tool, created by KONE [32].

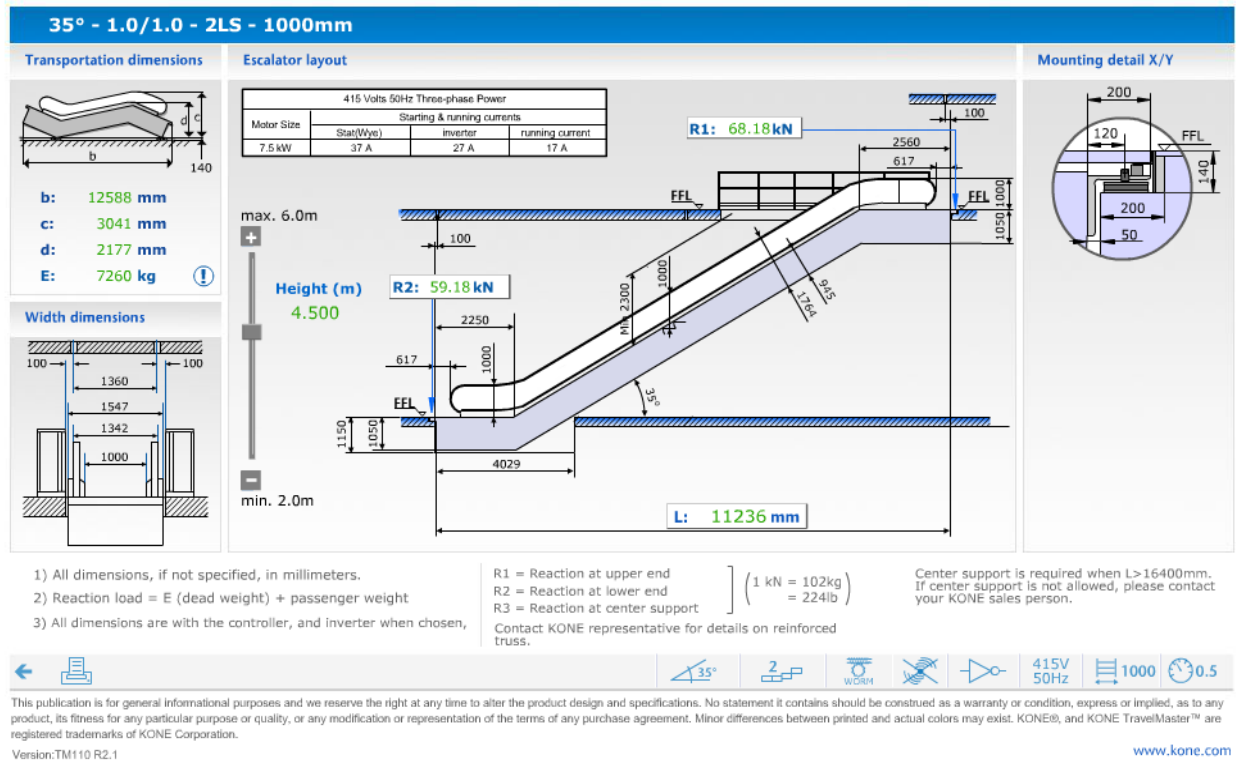


Figure 14: Design of the measured escalator, created with [32].

The opening hours of the department store where escalators were installed vary depending on the day of the week. During weekdays the store is open from 9 am till 9 pm. The escalators were switched on at least one hour before, and the personnel used them during this one preliminary hour. On Saturdays the store is open from 9 am to 6 pm, and on Sundays it is open from 12 to 6 pm.

3.3 Evaluation of the passenger speed

During measurements, speed of passengers was calculated in order to estimate the walking factor, mentioned in Section 2.7.2. Speed calculations were possible because the timestamp of each individual crossing the line and distance between lines were known.

Figure 15 illustrates the principle of speed calculation. Key assumption taken during speed calculation was such that, each person crossing the distance between the lines faster than the nominal speed of escalator (0,5 m/s) was assumed to continue walking with the same speed until he reached the top. The timestamps were collected with milliseconds precision during people counting procedure.



Figure 15: Principle of speed calculation.

4. Results

This chapter presents the results obtained from the measurements on the escalators on site. Short-term measuring device data is presented in the beginning, which forms the base for calculation and estimation of energy efficiency of the escalator according to ISO 25745-1 [22] standard. A detailed breakdown of the picture is demonstrated, including passenger data. Long-term energy consumption data is presented afterwards along with the distribution of traffic flow curves. Comparison of gained energy consumption profiles during different days: weekdays, Saturdays and Sundays; passenger's speed distribution and walking factor are introduced in the end.

4.1 Reference power measurements

The measurement device was installed according to description in the previous chapter and reference power measurements were carried under no load condition. Short-term power measurements from Fluke were taken on 13th of November, the day of installation. Fluke 1760 is able to take 5 measurements per second. Measurements were used as a reference for long-term measurements in order to do a correction.

Results of measurements presented in Table 3 below:

Table 3: Energy consumption of escalator during different modes, no load.

Power at stop mode, W	88
Power at slow-speed mode, W	844
Power at nominal speed without load, W	1720

Results of these measurements can be used for both escalators, these are the average values and for both of the escalators they were quite the same. According to [5], in the analyzed escalators the low-speed power ranged from 450W to 960W, while stop mode power from 42-84W.

Figures 16 and 17 show the typical power profile in various passenger situations. It is clearly shown that the more passengers boarding the upwards moving escalator, the more power it consumes. On the downwards moving escalator it is on the contrary, the more passengers boarding escalator, the less electric power it consumes. Measurements in these figures were extracted during the mass experiment, discussed in Section 4.3. It is seen from the figure, that on the downwards moving escalator, the heavier passenger consumed slightly less power, than lighter one. Fundamental behavior is present.

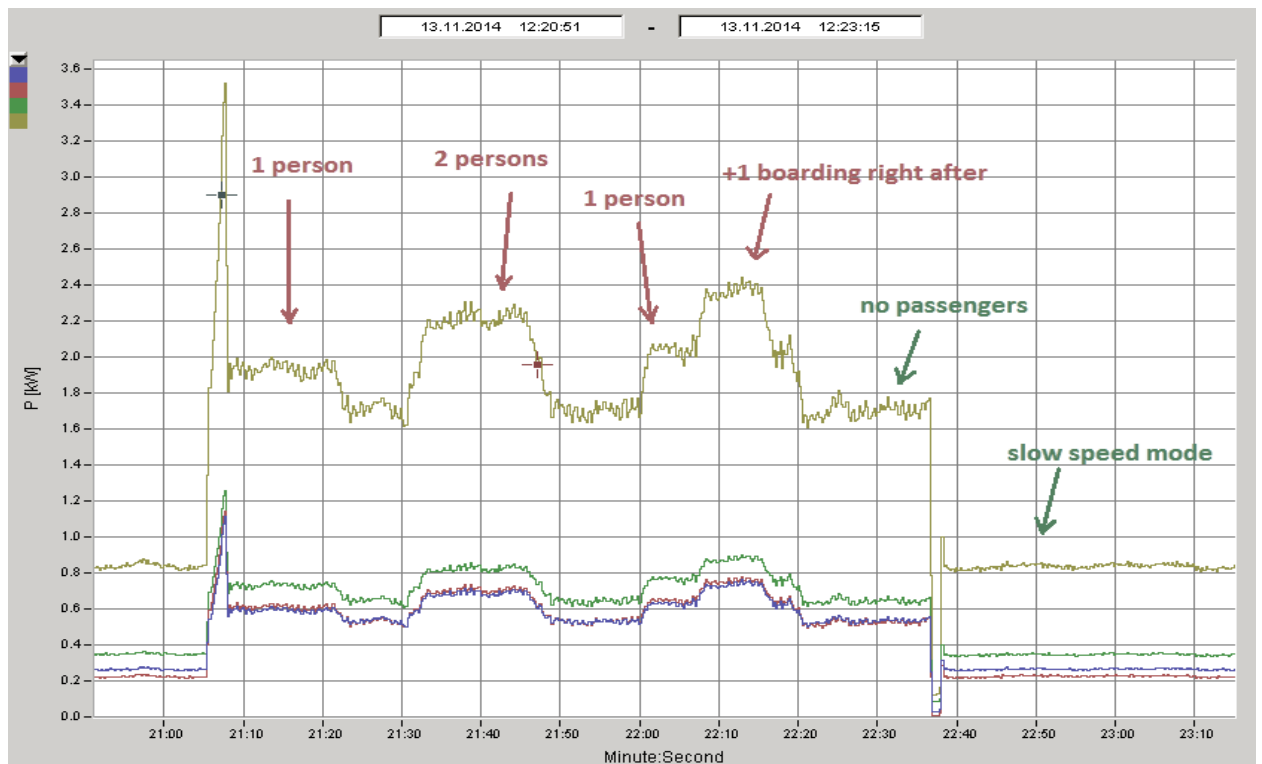


Figure 16: Fluke power breakdown picture for upwards running escalator.

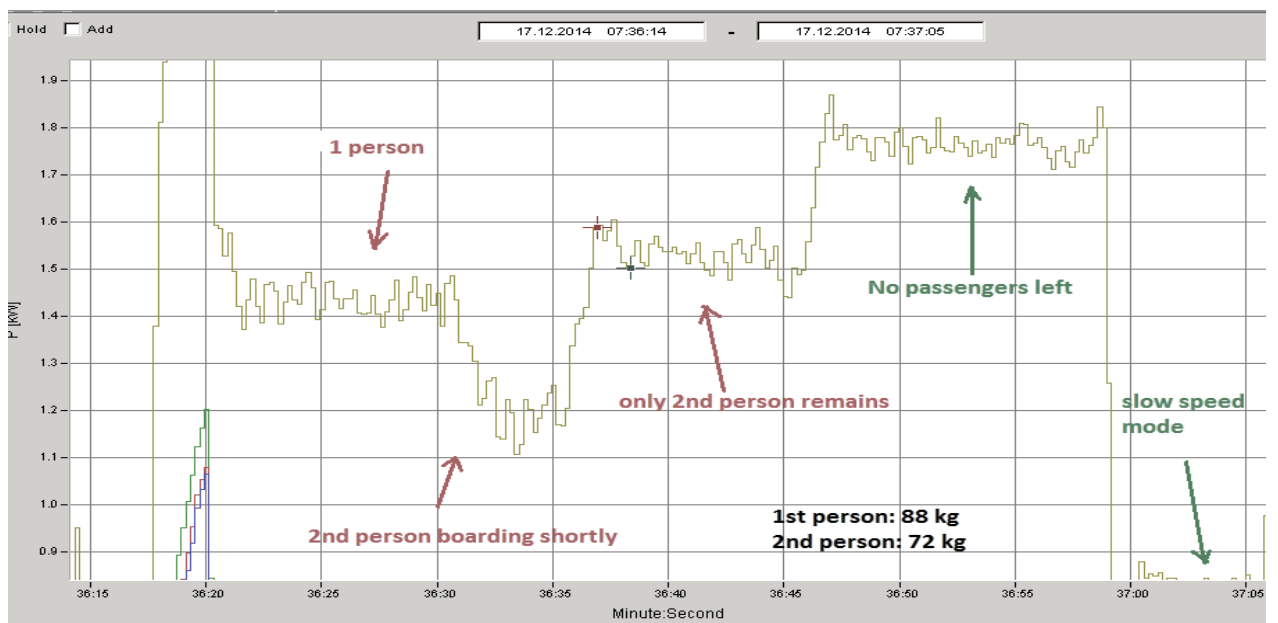


Figure 17: Fluke power breakdown picture for downwards running escalator.

4.2 Long-term measurements

This part introduces the data gathered with the long-term measurements setup.

4.2.1 Reliability analysis of long-term consumption data

Due to the issues with current clamps introduced in Sections 3.1.1 and 3.1.3, correction of values of the long-term measurements were done using values of short-term measurements.

Figure 18 below presents the error compensation factor, showing the size of error depending on the power measurements of the long-term setup.

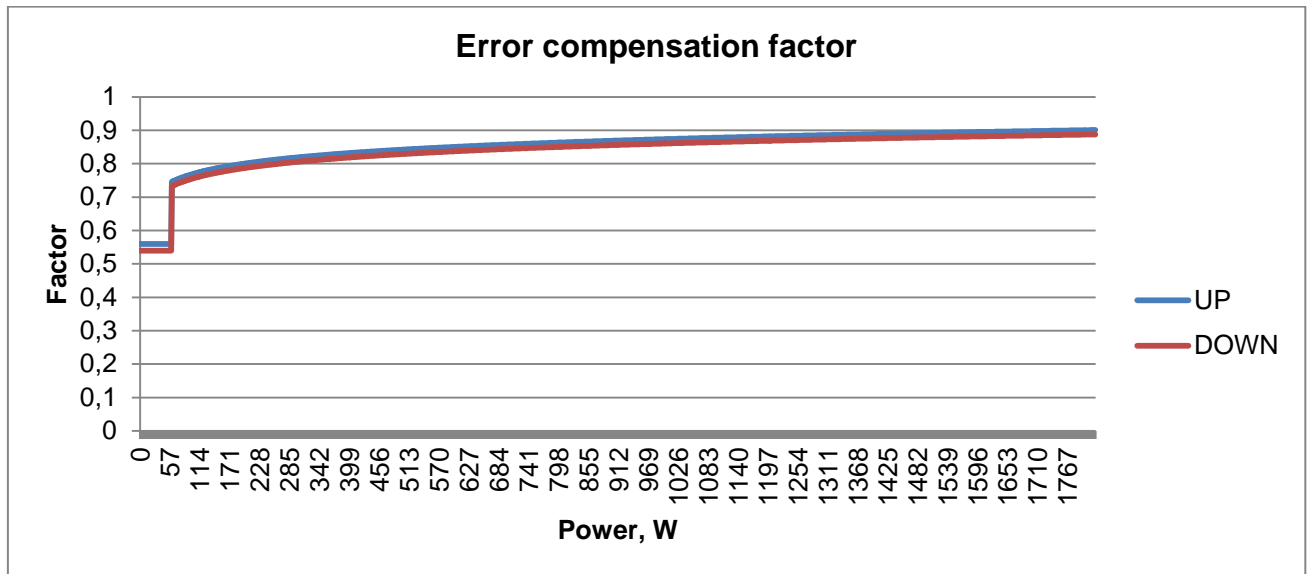


Figure 18: Error compensation factor.

A correction coefficient was withdrawn from data, resulting in a value change:

- For upwards: $P/0.56$ IF power under 60 W, the rest $P/(0.0454 \cdot \ln(P) + 0.56)$
- For downwards: $P/0.547$ IF power under 60 W, $P/(0.0454 \cdot \ln(P) + 0.547)$

Where P is average power consumption value

After compensation the data looks a lot more like the short term measurements; therefore, more accurate. Following figures show the comparison of compensated data to the original one and the Fluke data for upward and downward escalator.

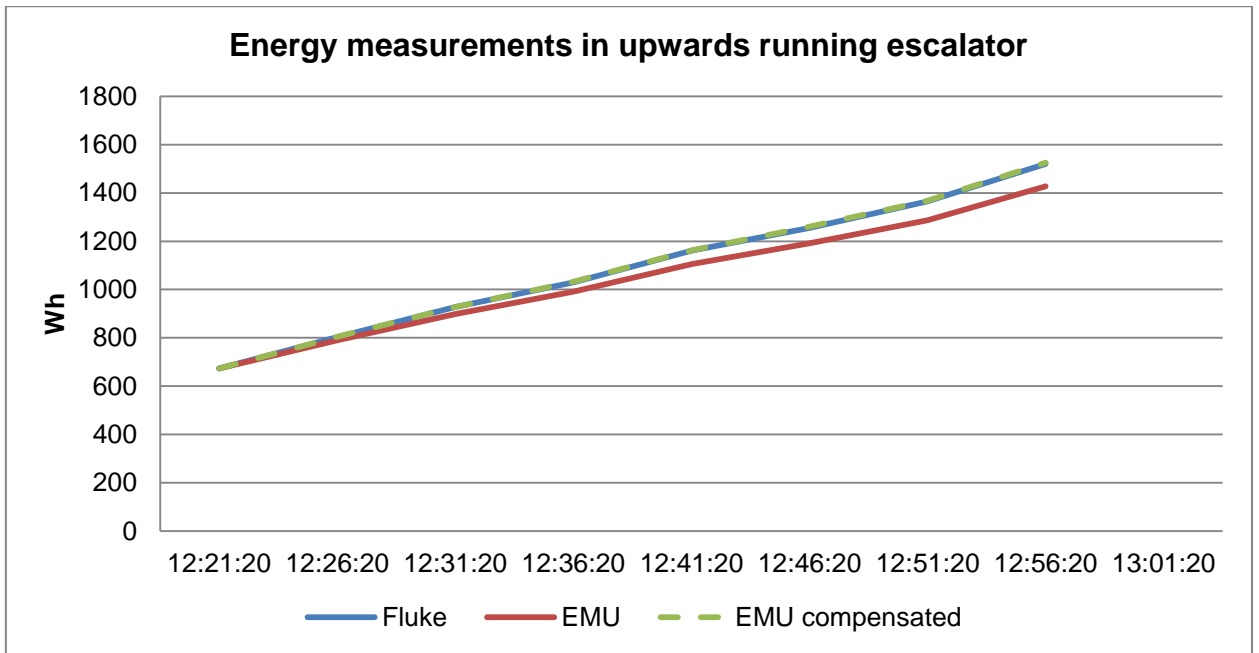


Figure 19: Error compensation for energy measurements in upwards running escalator.

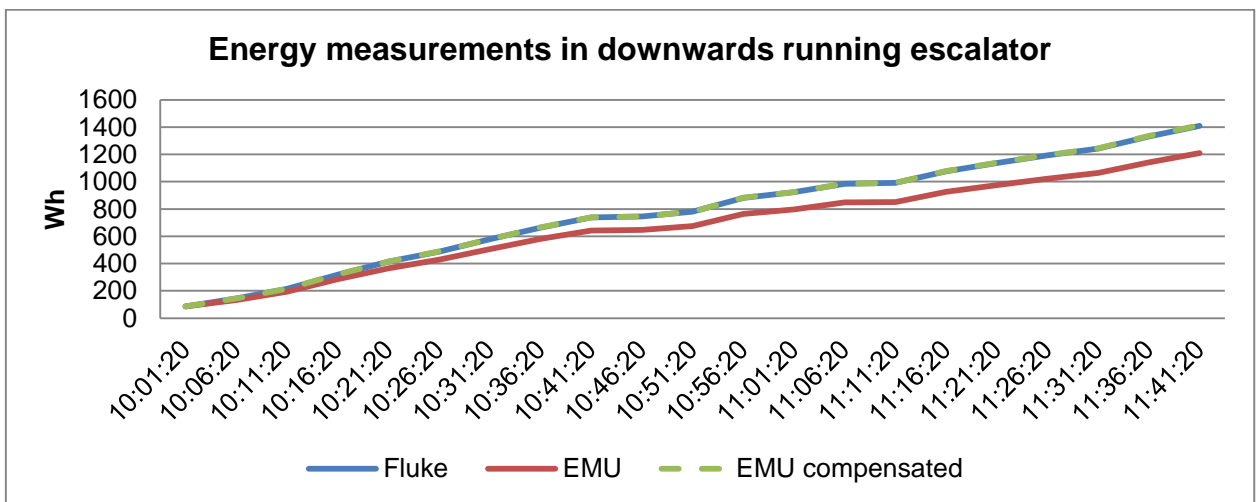


Figure 20: Error compensation for energy measurements in downwards running escalator.

4.2.2 Consumption over longer period

Measurements were carried out from 13th of November 2014 till 1st of January 2015.

Escalator usage over December 2014

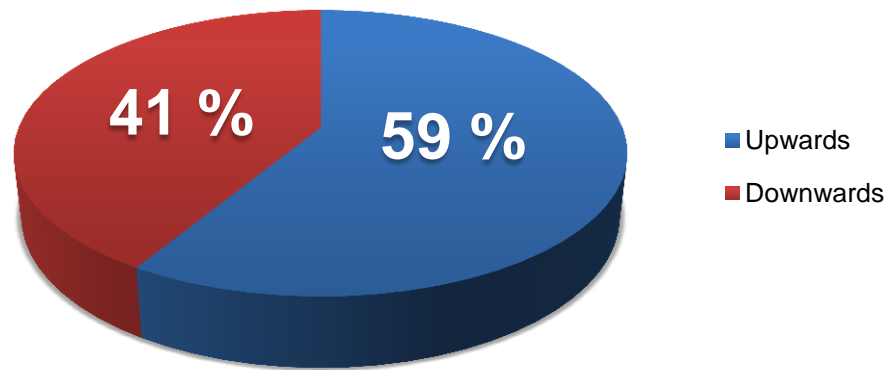


Figure 21: Usage and energy consumption division by escalators

Escalator usage was divided in favor of the upwards moving escalator, but there is no obvious reason for that. The store has two floors, and in order to get from one to another escalator is the only way, unless people walk out of the store to take stairs to the next floor. It is hard to say if passengers preferred to use the inside store escalator to get to the next floor of the shopping mall and didn't use it vice versa.

4.2.3 Energy and power profiles

One of our main measurement targets was energy consumption over a full day. Energy consumption during different times of the week is different. Moreover, the opening and closing hours of the store department also vary. In our case the opening hours on the weekdays were from 09:00 till 21:00, Saturdays from 09:00 till 18:00 and Sundays from 12:00 till 18:00. In reality, the escalator pair was switched on at least an hour or two earlier, when the first personnel arrived in order to prepare the shop prior to opening. Due to the above, three-day type segregation is used in this thesis.

Following figures present the electricity consumption of upwards and downwards escalators in 5-minute averages on weekdays.

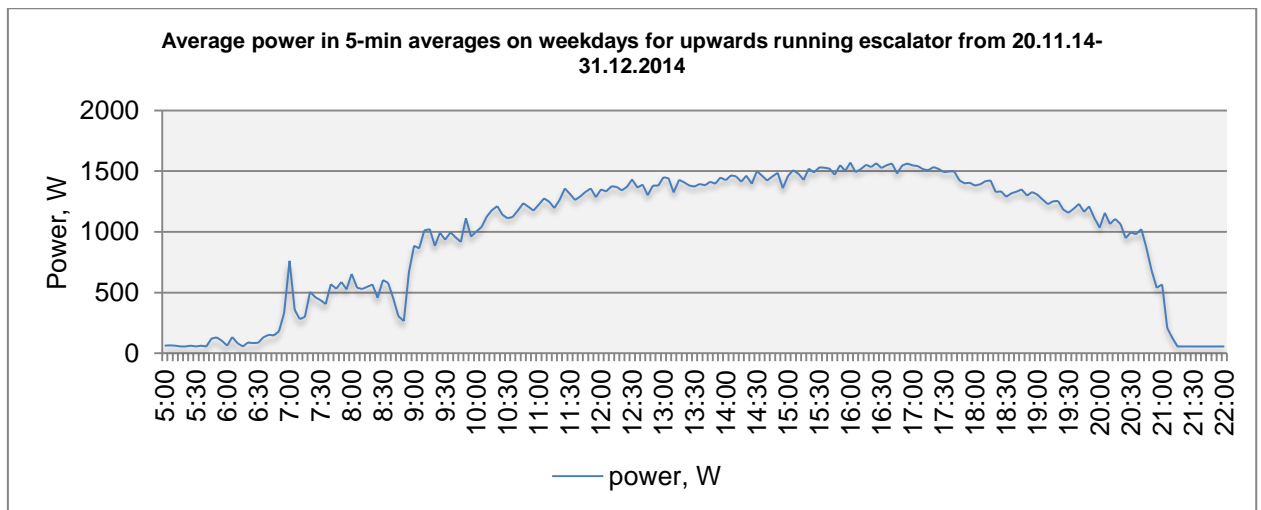


Figure 22: Average power on weekdays for upwards running escalator.

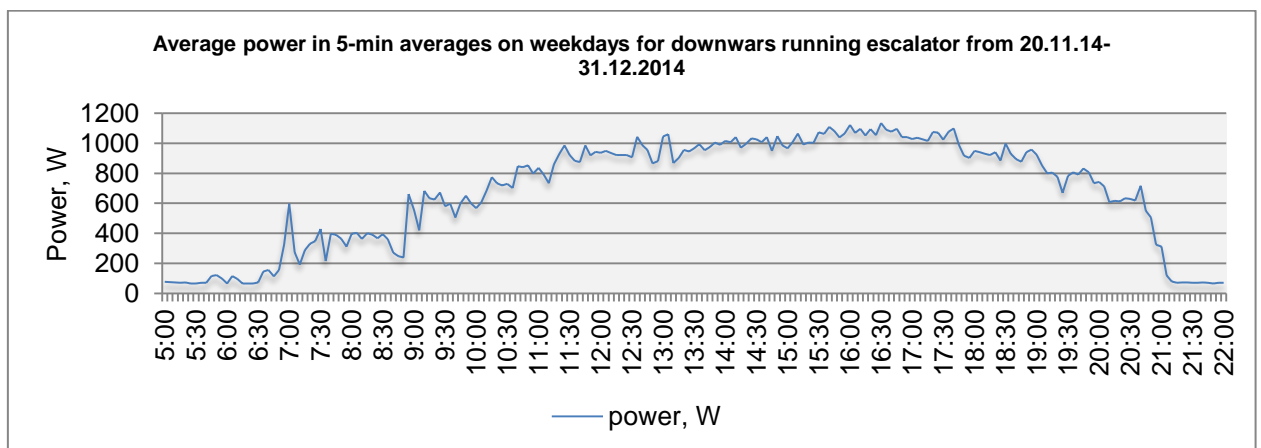


Figure 23: Average power on weekdays for downwards running escalator.

In Figures 23 and 24 first shoots of power are due to personnel using the escalator, while it is still warming up. Power takes a dip prior to the opening before first customers. Average power consumption grows steadily and peaks around 15:50 – 17:30, deteriorating further to the closing minutes on both escalators.

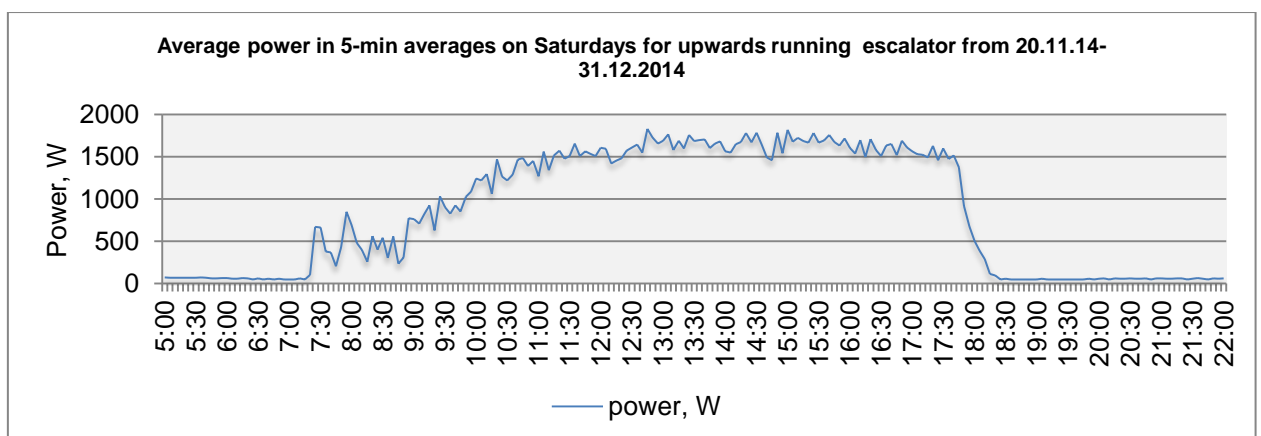


Figure 24: Average power on Saturdays for upwards running escalator.

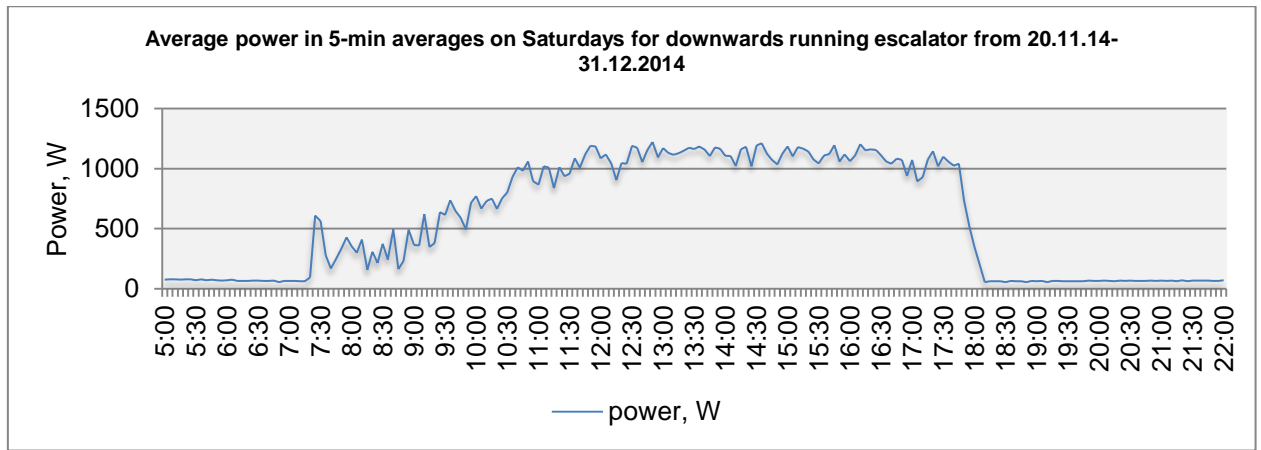


Figure 25: Average power on Saturdays for downwards running escalator.

In Figures 24 and 25 average power consumption grows steadily after opening and peaks around 12:30 and 15:00, deteriorating further to the closing minutes.

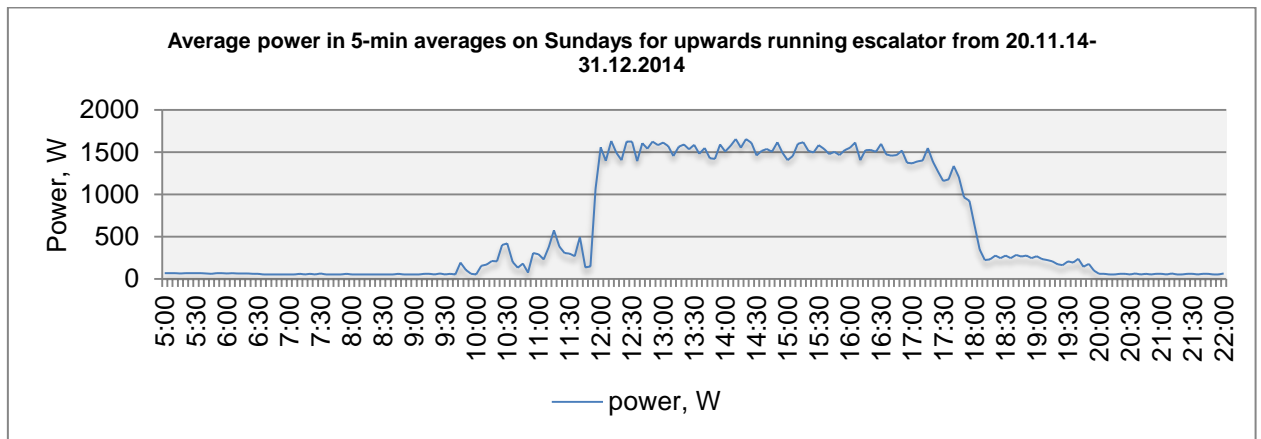


Figure 26: Average power on Sundays for upwards running escalator

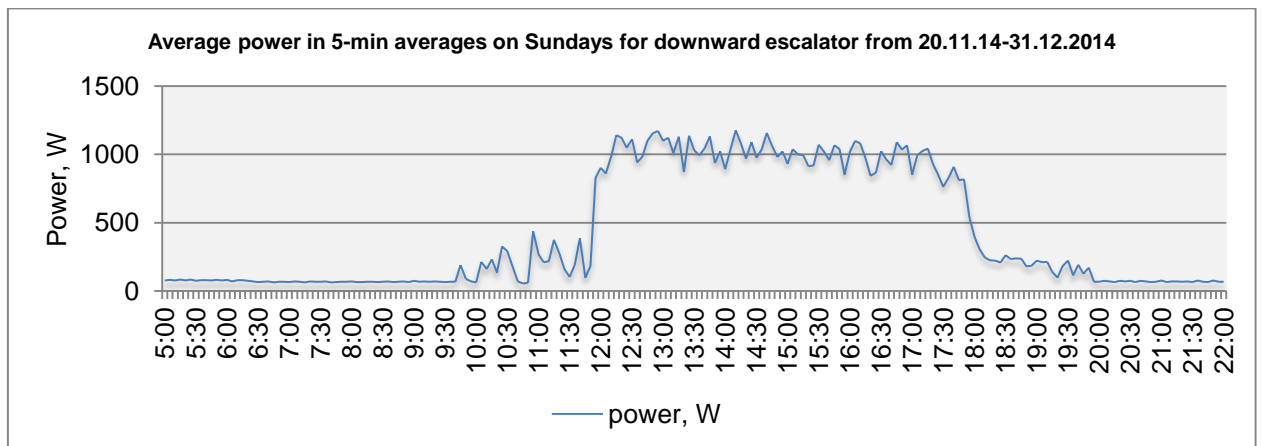


Figure 27: Average power on Sundays for downwards running escalator

In Figures 26 and 27 average power consumption grows rapidly after opening and peaks around opening time 12:00 – 12:30, stays relatively steady until around 16:00, deteriorating further to the closing minutes. Power consumption after 18:00 is presented here due to extended opening hours of the stores in Finland approaching Christmas.

Overall, we see that the behavior of the average power consumption curve on downwards escalator is more volatile than of the upwards. We can also note that the shape of figures is very similar, it's just that the total average value and the amplitude is lower on the downwards escalator, because it is recovering the potential energy stored in the passengers and is also less used, as can be seen from figures below.

Following figures present passenger data during same week segregation.

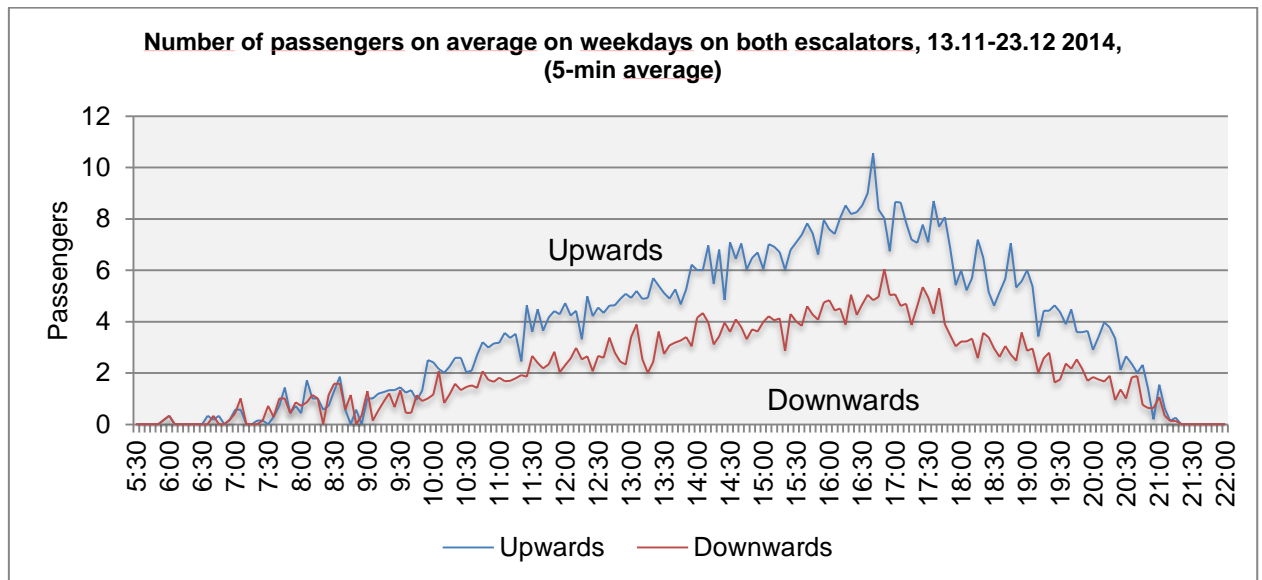


Figure 28: People flow on both escalators during weekdays.

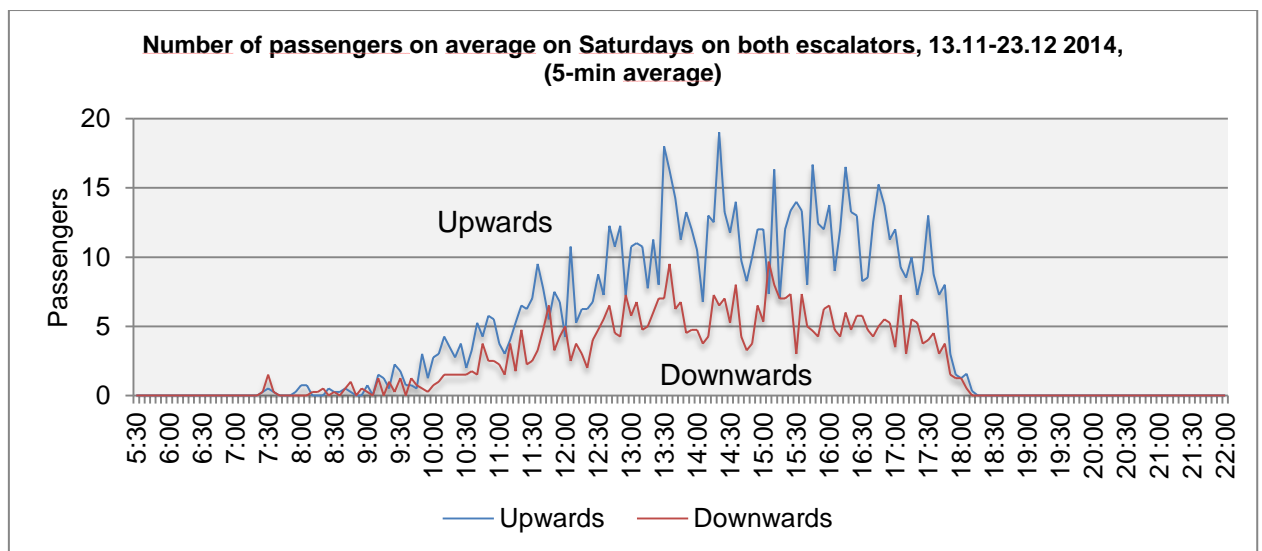


Figure 29: People flow on both escalators during Saturdays.

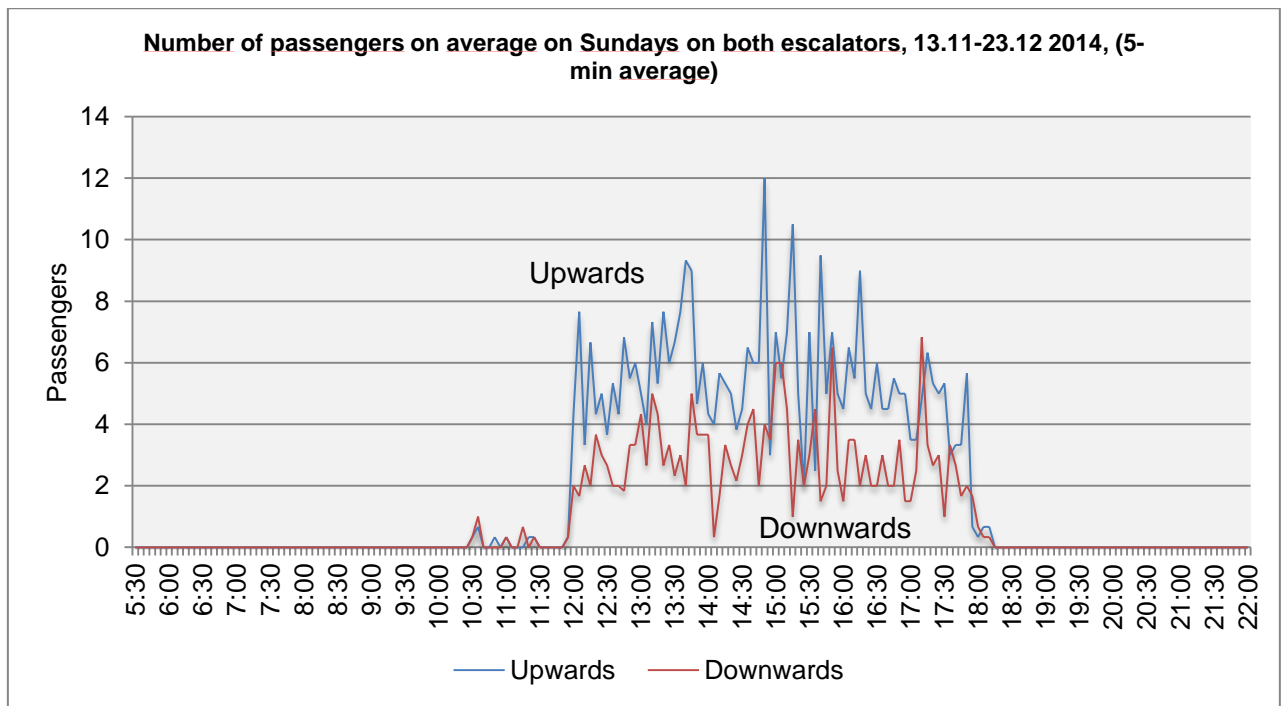


Figure 30: People flow on both escalators during Sundays.

Figures 28, 29 and 30 show people flow profiles of both upwards and downwards moving escalators in 5-minute average graphs. In these figures we can see that at peak times there are almost twice more people using the upwards moving escalator than the other. Weekday curves have very similar shape and peak times for both escalators match together. Saturday and Sunday curves are more volatile due to the fact that there is much less data for weekends than weekdays.

In order to present distribution of traffic flow during a day in relation to energy three days were chosen: Friday 28.11.2014, Saturday 29.11.2014, Sunday 30.11.2014. Following figures present data of these days first for upwards escalator.

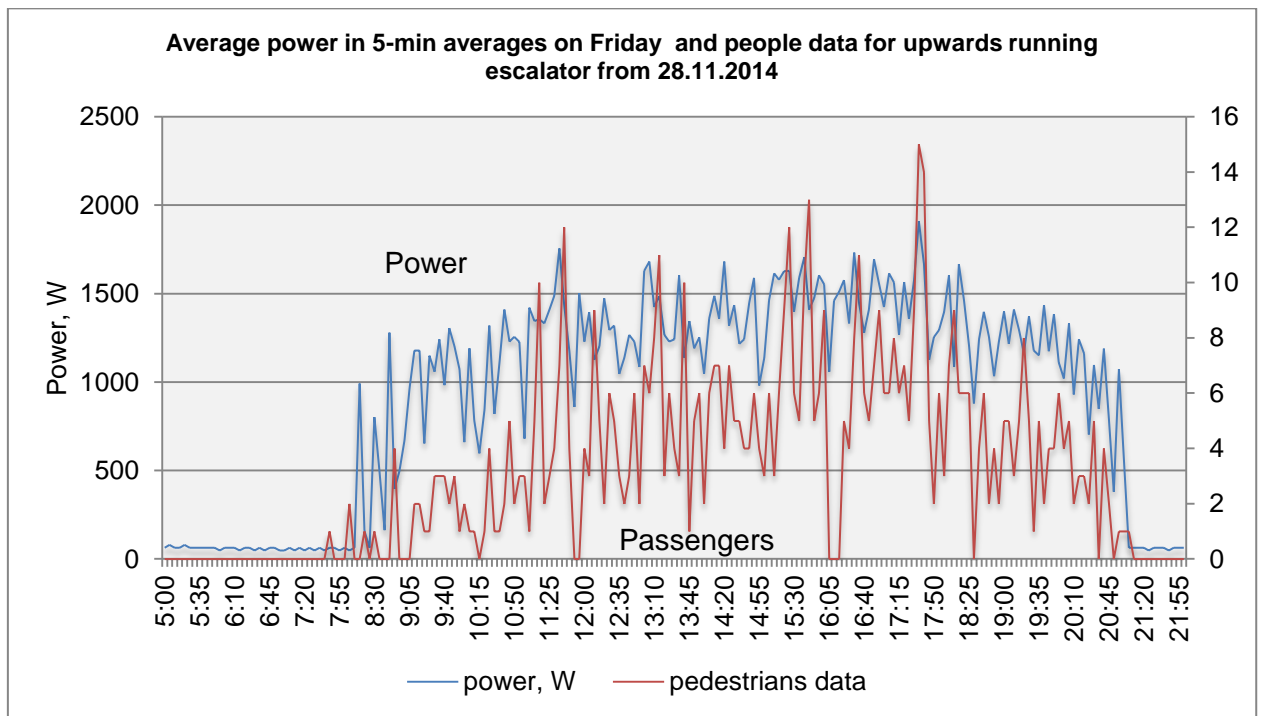


Figure 31: Average power and passenger data in 5-min averages for upwards running escalator on Friday 28.11.2014.

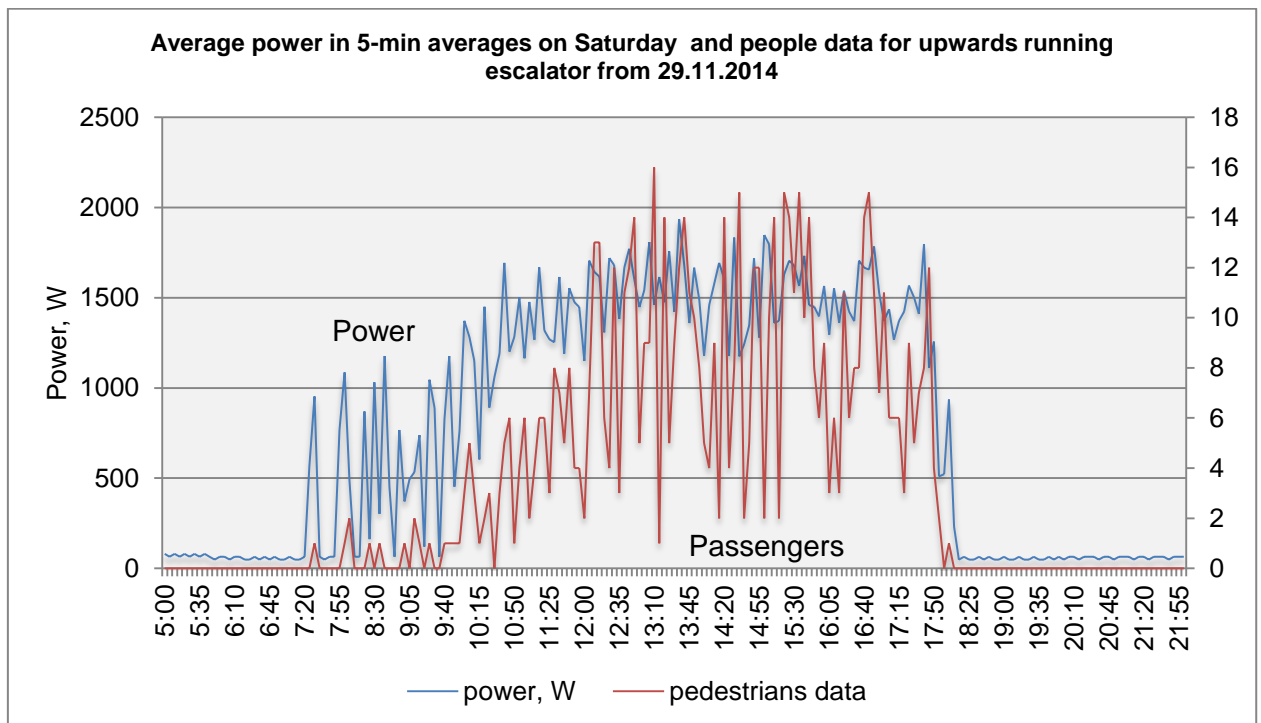


Figure 32: Average power and passenger data in 5-min averages for upwards running escalator on Saturday 29.11.2014.

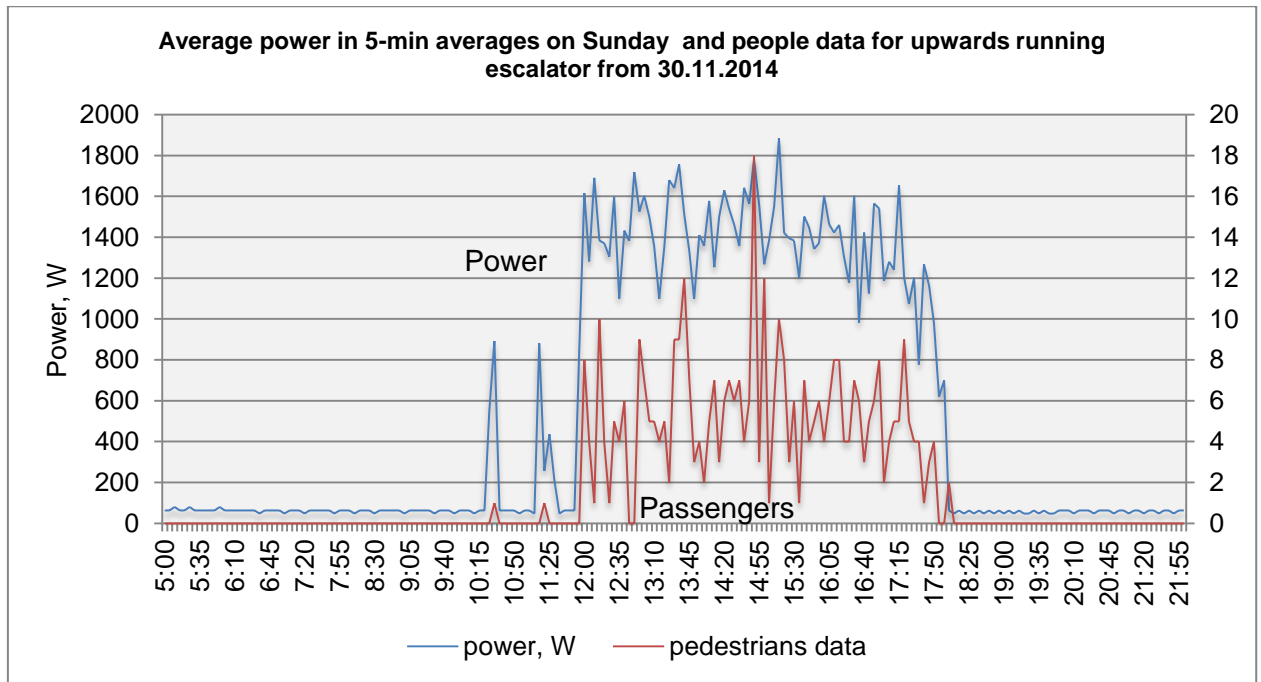


Figure 33: Average power and passenger data in 5-min averages for upwards running escalator on Sunday 30.11.2014.

In Figures 31, 32 and 33 we can see that the shape of average power consumption curve corresponds well to the one presented earlier in respective curves of weekdays, Saturdays and Sundays over the examined period. For the upwards escalator the peak of people flow corresponds with the peak of power consumption. It is also notable that even smallest spikes in people flow cause relatively large spikes of power consumption. Spikes of people flow before the store opening are caused by personnel's rare travels on the escalator and preparation to the store opening.

Following figures present average power consumption together with people flow data over same days on the downwards escalator.

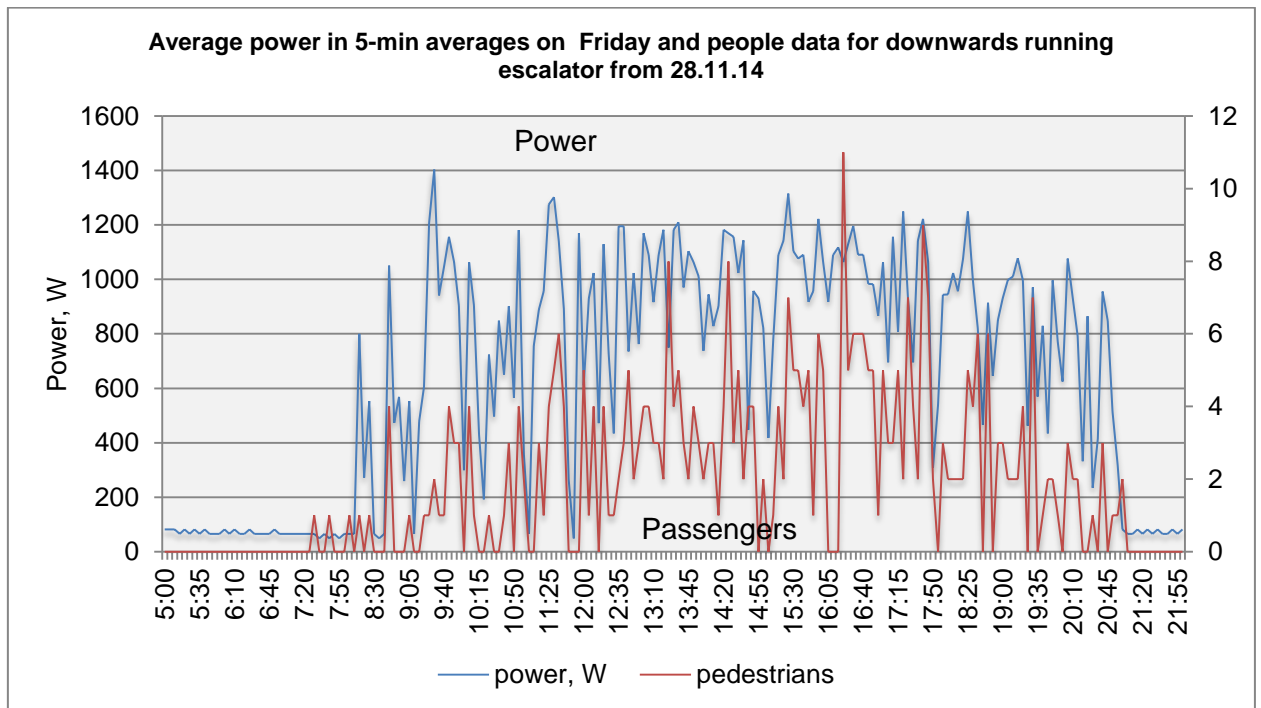


Figure 34: Average power and passenger data in 5-min averages for downwards running escalator on Friday 28.11.2014.

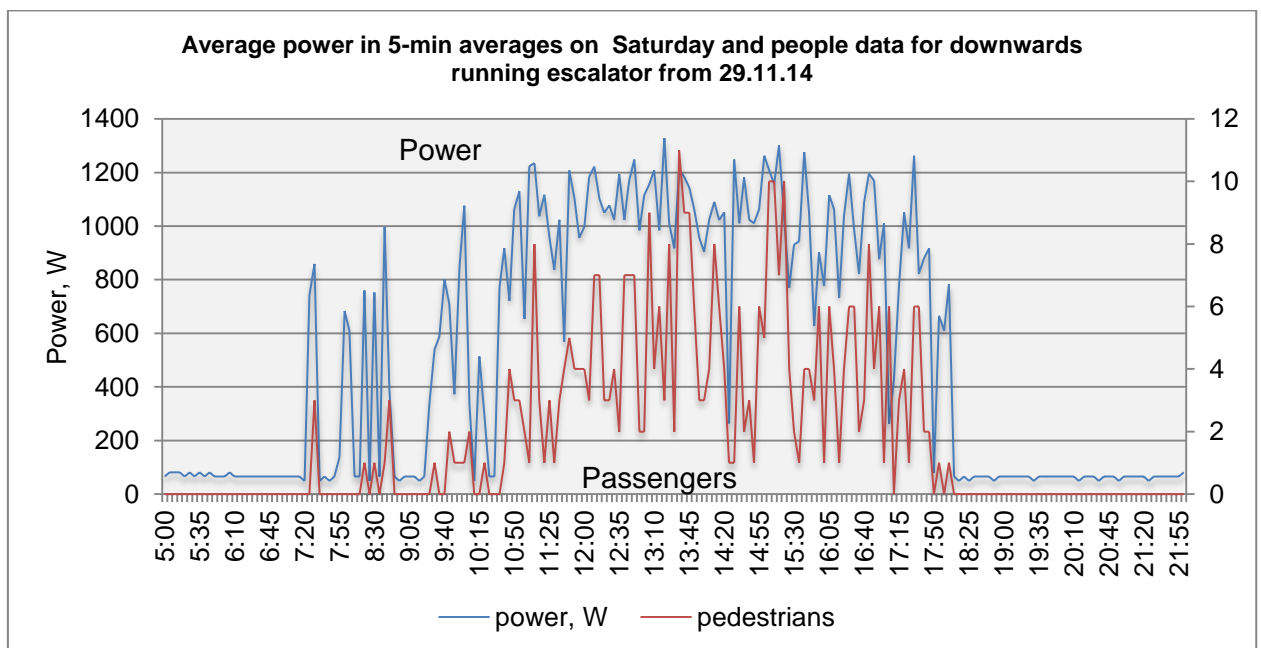


Figure 35: Average power and passenger data in 5-min averages for downwards running escalator on Saturday 29.11.2014.

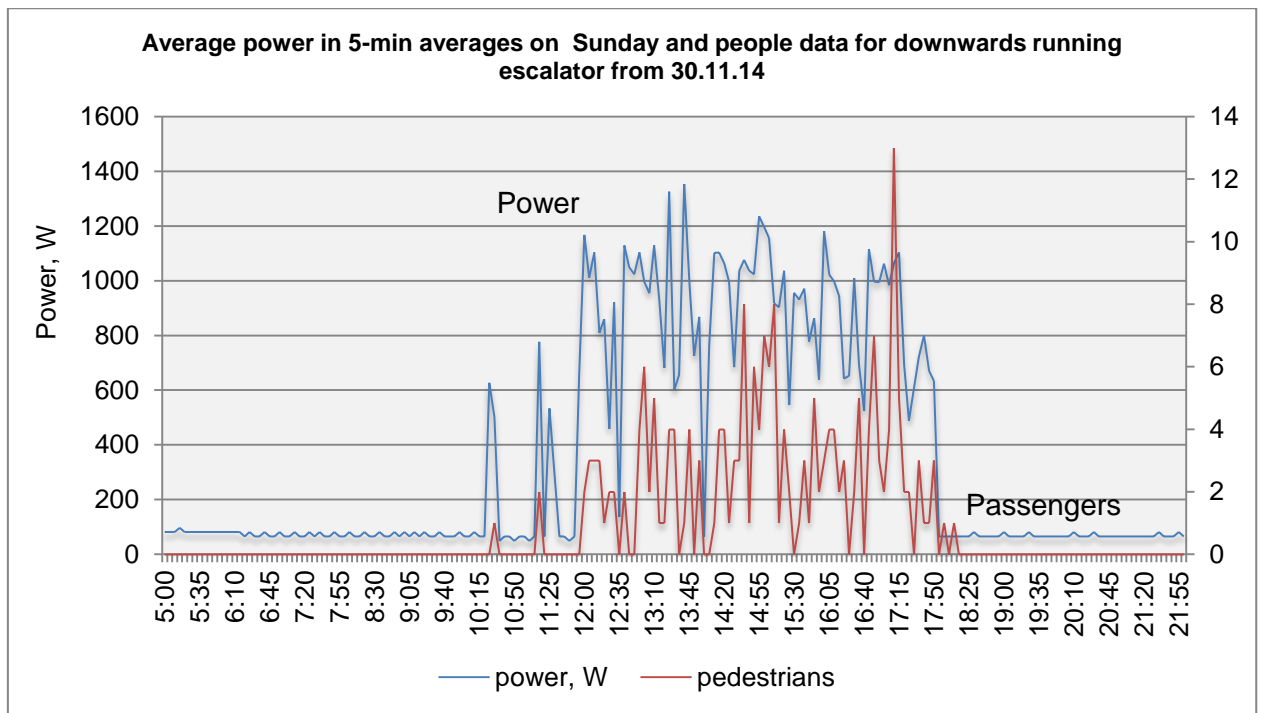


Figure 36: Average power and passenger data in 5-min averages for downwards running escalator on Sunday 30.11.2014.

It is notable that from Figures 34, 35, 36 and also from the average power curves during a number of days, that the obvious impact of larger numbers of passengers on the profile of the power curve is not so clear. It is known that with larger numbers of passengers that use the downwards moving escalator power consumption should be lower than in the same people flow frequency, but fewer passengers. This can be illustrated with a diagram from downwards escalator [10] where the method of deriving fixed losses from the constant speed escalators was introduced.

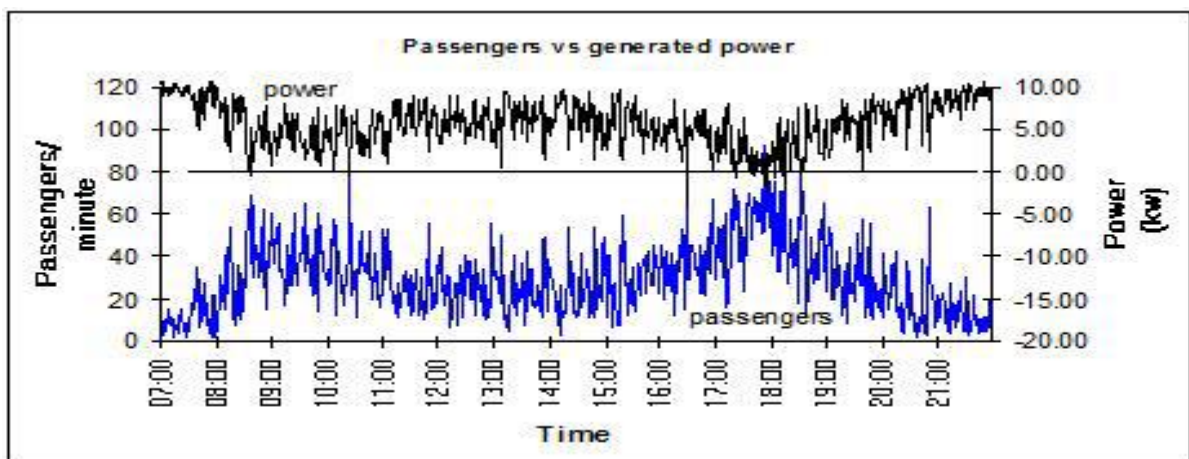


Figure 37: Power trace and passenger trace from [10].

Our data shows different correlations, but in our case escalators are equipped with power saving modes: slow-speed and switch-off. From the Fluke data in Figure 17, taken while power vs mass test was conducted, we can clearly see the fundamental behavior. Figure 17 shows how power values are affected by passengers. The first

passenger is 16 kg heavier than the 2nd. They board escalator with around 8 second time difference and it is clearly seen that power consumption is lower while 1st passenger is on board in comparison to the 2nd one. However, this is only a single occasion situation.

The explanation of steeper trends over day time periods are in power saving modes that are affecting the average curve. It is the time between two consecutive passengers that affects the average power.

4.2.4 The impact of power saving modes

The following figure represents a scatter plot of measured people flow of the upwards escalator in comparison to the time between consecutive passengers boarding the escalator. The plot for downwards moving escalator would be basically the same except first 16 second, where the power values would be smaller due to the effect of mass on downwards escalator. Figure 38 shows how average values of energy consumption in the figures in Section 4.2.3 depend on power saving modes activity.

When there is no or small amounts of time between consecutive passengers and the power flow is constant, the average consumption is at its highest. First of all, when the time doesn't exceed 16 seconds, the escalator is constantly carrying a load of an average weight. As soon as the time pause between passengers excels, there happens a moment when escalator runs a portion of time without passengers, which takes less power consumption for upwards and vice versa for downwards escalator. When the time between consecutive passengers outreaches 30 seconds, the escalator turns into slow speed mode, decreasing energy consumption greatly. This is why there are no peaks of consumption at times with low people flow on both escalators, and especially on the downwards moving one. Figure 38 illustrates why our power flow curves are related to people flow during model days in such a way.

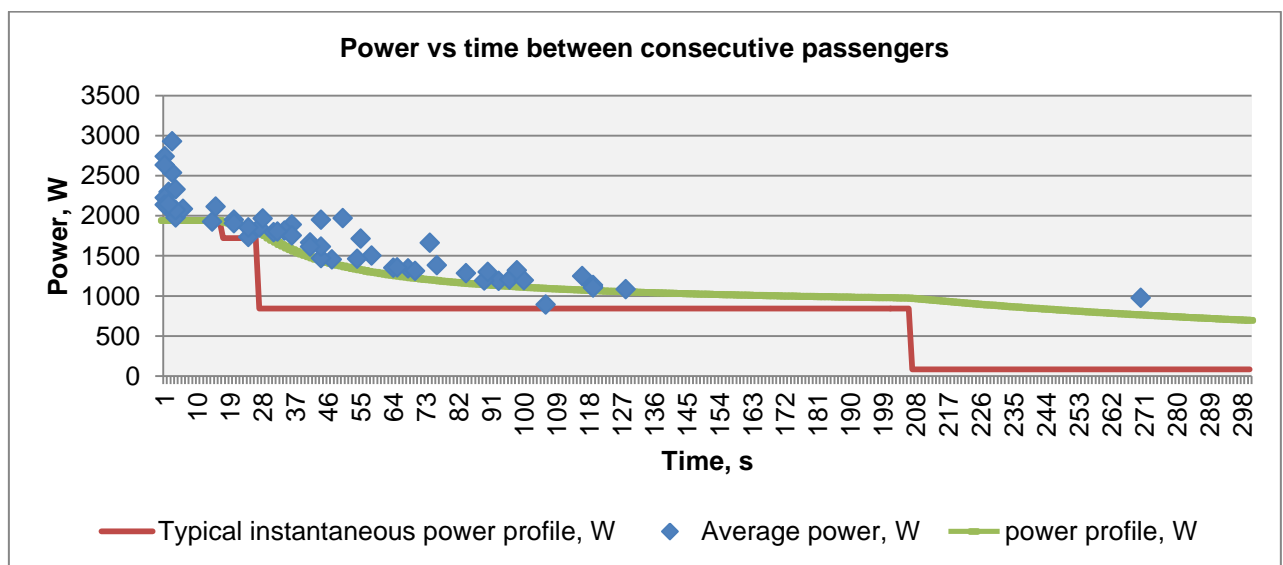


Figure 38: Power vs time between consecutive passengers on upwards escalator.

In this picture, the typical power profile is the typical momentary power profile, which takes place when one person boards the escalator and is transported on top without him walking on the escalator. When there is a group of persons, the power during their travel time is increased as presented in the next section, Section 4.3. This also explains the high scatter plot power values near the 0 second time between passengers in the above figure. Average power is the scatter plot of the average power consumption measured between consecutive passengers in relation to the time between them. The green line is the theoretical average power profile based on typical momentary power profile. Basically, with increased time between consecutive passengers the average power curve values are following the theoretical average power profile curve (green),

which has a direct impact on the shape of the average power profile curve and its peaks.

4.3 The impact of passenger load

This section gives an overview of the test conducted on the escalators using pre-determined masses and its results with relation of consumed power and transported mass.

An experiment was carried out on 17th of December 2014. During it, a series of tests was carried out on both escalators, where different masses were carried on the escalator in order to understand better the relation between power consumption and mass and to be able to determine variable consumption of escalators.

From this experiment, the following scatter plots were formed.

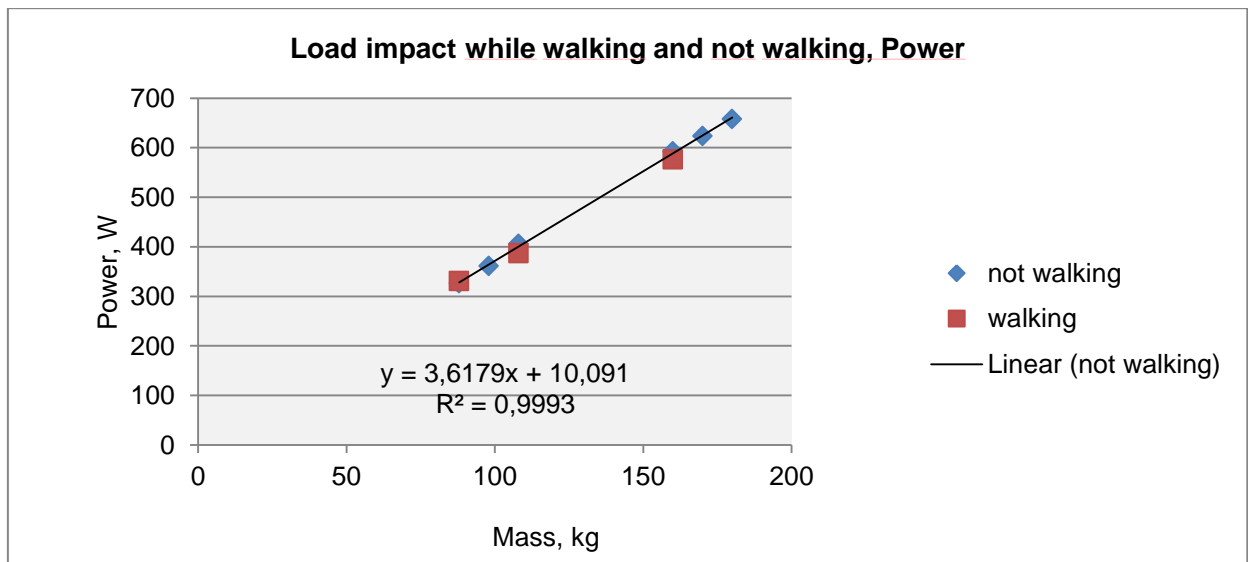


Figure 39: Scatter plot of power vs mass relation on upwards running escalator.

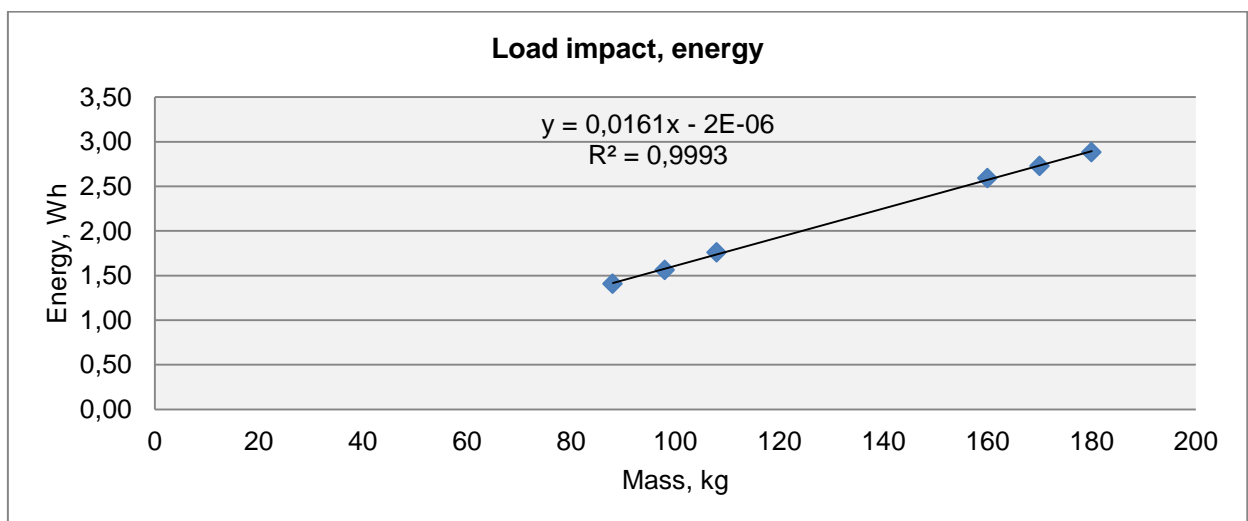


Figure 40: Scatter plot of energy vs mass relation on upwards running escalator.

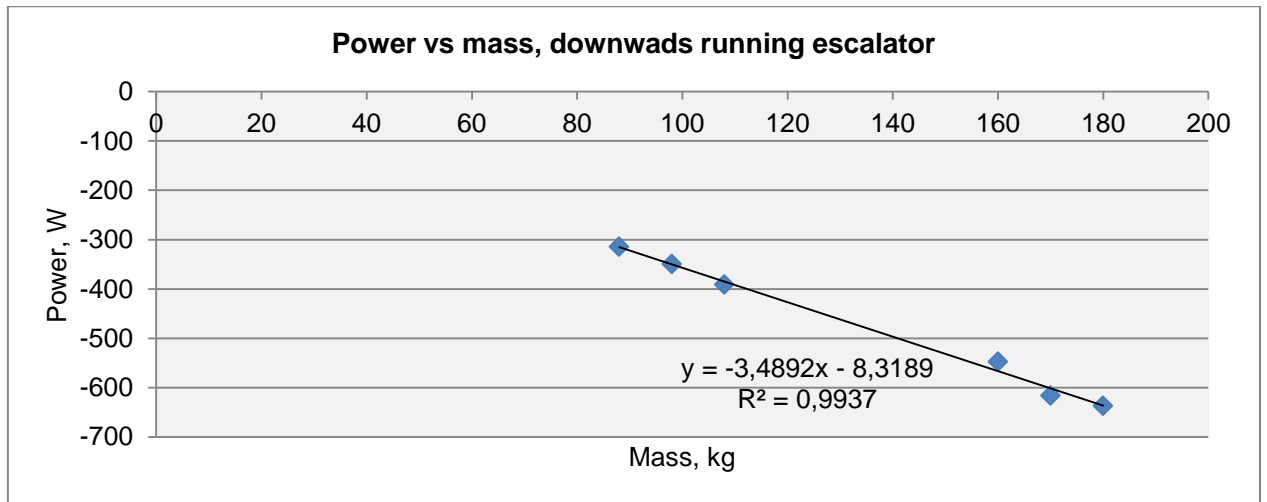


Figure 41: Scatter plot of power vs mass relation on downwards running escalator. Standing.

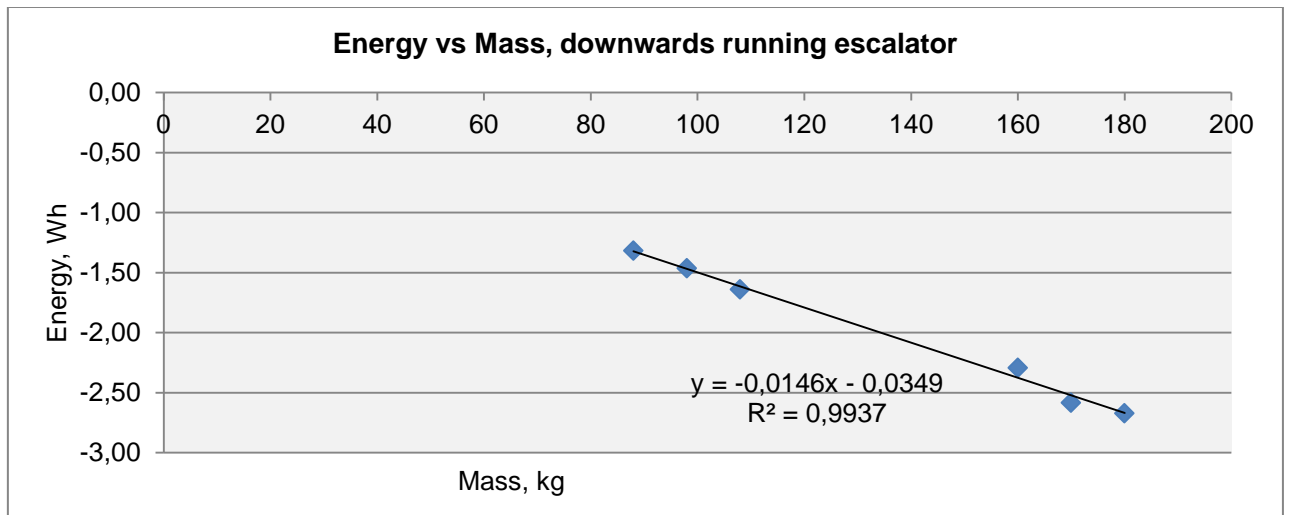


Figure 42: Scatter plot of energy vs mass relation on downwards running escalator. Standing.

In Figures 39, 40, 41, 42 we can see that the relation is linear and the correlation factor has a value of 0,99. It takes approximately 0,0161 Wh to get 1 kilogram of mass on top of the escalator, and we save approximately 0,0146 Wh for each additional kilogram of mass on downwards escalator while it is running.

The impact of each person on the variable energy consumption in a 5-min average curve in the running mode can be calculated the following way:

For the upwards escalator:

$$3,62 * m * \frac{t}{300} * k_{wf} = 3,62 * 75 * \frac{16}{300} * 0,8 = 14,48 * 0,79 = 11,43 \text{ W (5)}$$

For downwards escalator:

$$-3,5 * m * \frac{t}{300} * k_{wf} = -3,5 * 75 * \frac{16}{300} * 0,87 = -12,24 \text{ W (6)}$$

Where, m – is the average people mass [kg], t – time taken to reach the end destination, k_{wf} – walking factor.

The average mass is considered to be 75 kg, the time that it takes to reach the top was measured and is 16 s. The walking factors for each escalator were calculated in different way than introduced in Section 2.7. The fact that we knew the speed of each passenger allowed to use the following formula:

$$k_{wf} = \frac{v_e - v_p}{v_e}; (7)$$

Where, v_e – speed of the escalator [m/s], v_p – speed of the passenger [m/s].

The walking factor was calculated to be 0,79 and 0,87 on average for upwards and downwards escalator respectively.

It is seen from figures in Section 4.2 that the impact of variable energy consumption in the situation of the current escalator is not large. The amount of people on average did not excel 20 persons in one 5-min slot.

With these equations, the effect of walking was calculated and presented in Section 4.4.

4.4 Walking passengers - The effect on the energy consumption

As explained in previous studies in Section 2.7 – walking on escalators does not introduce any dynamic impact. Figure 43 illustrates the situation when a person is stationary on the escalator (on the left) and shows the difference with the situation when a passenger is walking. These figures were taken from Fluke 1760 data test, conducted on 17th of December 2014, during the mass experiment. We can clearly see that in the figure, where the values of power are the same, while only length of the time period is different. A walking person on the upwards escalator clearly spends less time on it and therefore, spends escalator consumes less energy. It can be seen that the power while walking is slightly more varying, but the average power same as seen in Figure 39. There is an opposite effect on the downwards escalator.

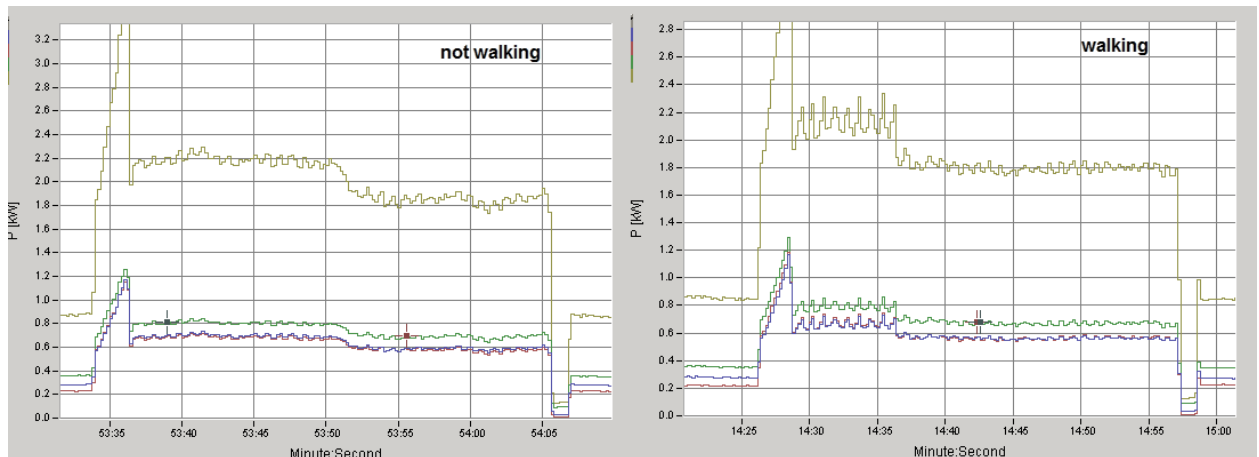


Figure 43: Effect of walking.

In our measurements, the walking factor was calculated and turned out to be 0,79 for upwards moving escalator and 0,874 for downwards moving.

In order to calculate the effect of walking on electrical energy consumption of each escalator it is necessary to use load impact coefficients from equations in plots of the Section 4.3:

For upwards moving escalator:

$$0,0161 * (1 - k_{wf}) * N * m; (8)$$

For downwards moving escalator:

$$-0,0146 * (1 - k_{wf}) * N * m; (9)$$

Where k_{wf} is walking factor, N - average number of people per day, m - average mass of people.

Results of the calculation are presented in the following table.

Table 4: Savings per day due to passenger walking.

Escalator	Number of people	k_{wf}	Savings, Wh/day
Up	584,94	0,79	154,26
Down	327,82	0,87	-47,04

The average number of people was calculated from the acquired data during measurements and the average walking factor was calculated with Equation 7.

Effects of walking were already pictured in previous studies and discussed in Section 2.7. The net result of walking during a day on both escalators of the pair is around 100 Wh/day. Results indicate that, even without knowing the daily consumption of the whole escalator pair, these savings are very small to be meaningful. Reasons affecting it are mostly the small amount of people daily and inconsistency of the people flow. Typically on such escalators, in the store, if there is a group of people in front of the person- he is not likely to go walking to get on top faster, which happens often in metro stations. Perhaps, another pair of reasons for smaller amounts of walking people downwards is the fact that it is not so comfortable to do because the height of steps is different from an ordinary staircase and also not very safe. Results of escalator power consumption are given in Section 4.6.

4.5 Acceleration and deceleration - Effects on the power consumption

Effects of acceleration and deceleration power and energy consumption have to be taken into account. Time it takes an escalator to accelerate and decelerate depending if it was in the slow speed mode or stop mode is different. Results of calculation are presented in Table 5.

Table 5: Effects of acceleration and deceleration on peak consumption

Stop to nominal to slow-speed mode			
	Power, W	Time, s	Energy, Wh
Acceleration	2081,66	4,50	2,60
Deceleration	-1612,00	1,40	-0,63
		Difference	1,98
Slow to nominal to slow-speed mode			
Acceleration	1614,40	2,50	1,12
Deceleration	-1612,00	1,40	-0,63
		Difference	0,49

Where, Power is the average power value in watts compared to the previous mode, Time is the time in seconds that it takes for the escalator to accelerate or decelerate, and Energy is calculated energy consumed by the escalator during acceleration or deceleration in watt hours. The base level for power was retrieved from Fluke data and electrical power consumption during stop mode had to be subtracted from the value.

Table 5 reveals that time when acceleration happens from the stop mode, it takes around 2 more seconds for escalator to increase the speed and overcome the starting friction. As soon as the escalator slows down from the normal speed to slow-speed mode there is a 1,4 second deceleration taking place. The mutual effect of acceleration and deceleration is calculated to be 1,98 Wh from the stop mode and 0,5 Wh from running mode.

It was not in the scope of this thesis to record the amount of triggers of each state of the escalator pair. Nevertheless, a preliminary glimpse to more thoroughly analyzed people flow data, generated for upcoming studies, suggests that the amount of triggers from stop mode is around 45 and from slow-speed mode around 350 for an average weekday, which is calculated to be around 89 Wh and 172 Wh respectively. The total daily effect on average is 261 Wh for upwards escalator on an average weekday. This is comparable to effects of walking on escalators, presented in Section 4.4. The contribution to the total daily consumption of the escalator pair is roughly estimated to be less than 2%.

4.6 Electric energy consumption and energy saving effect

This section presents the comparison of the electricity consumption of the store and escalator pair for one month. Estimated calculation of impact of energy saving technologies is presented here.

4.6.1 Electric energy consumption of an escalator pair

A comparison of the electricity consumption level of the escalator and the whole store is presented below. It is remarkable that in a relatively small store, which has 2 floors and no specific technology except lighting and HVAC system, electricity consumption of the escalator pair (upwards moving and downwards moving escalators) daily is only 5% from the total consumption of the store. Information is presented in Figures 44, 45.

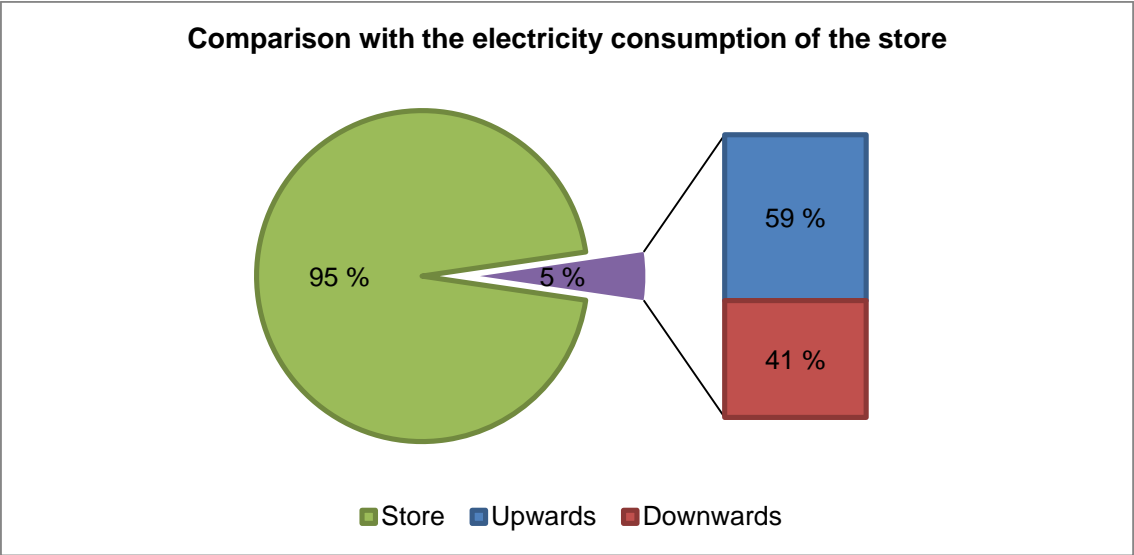


Figure 44: Comparison of electricity consumption of the escalator pair to the store.

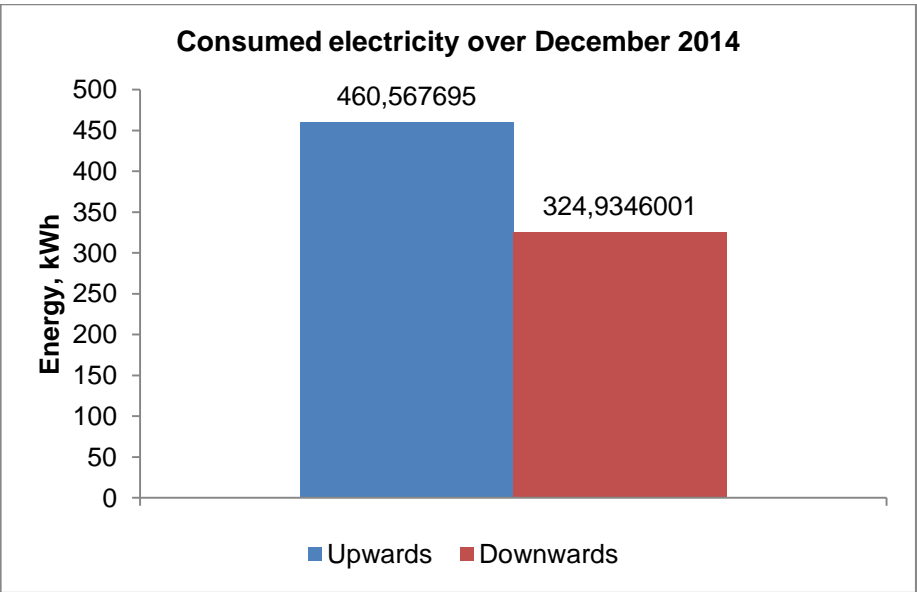


Figure 45: Electricity consumption of each escalator.

Total escalator pair consumption during December 2014 is 785,5 kWh, while electricity consumption of the store was 16869 kWh. The average consumption during a day is 28 kWh. Unfortunately, it is impossible to tell from the information we possess what contributes the most of energy consumption of the store.

4.6.2 Energy saving effect

Effects of energy saving technologies: slow speed and switch-off modes were calculated. Knowing the consumption during a no-load operation, it is possible to assume the electricity consumption of the escalator without energy saving modes. Days when the store was closed had to be excluded from the consumption profile. For upwards escalator, consumption was calculated to be 449,9 kWh. Estimated electricity consumption of the same escalator without energy saving modes is calculated to be 569,6 kWh. Saving ability of installed technologies is calculated to be 21,01% for the upwards escalator. The difference is presented in the Figure 46.

The reason why the figure is shaped differently from figures presented in Section 4.2 is because it includes also Saturdays and Sundays apart from weekdays, which shape the figure this way.

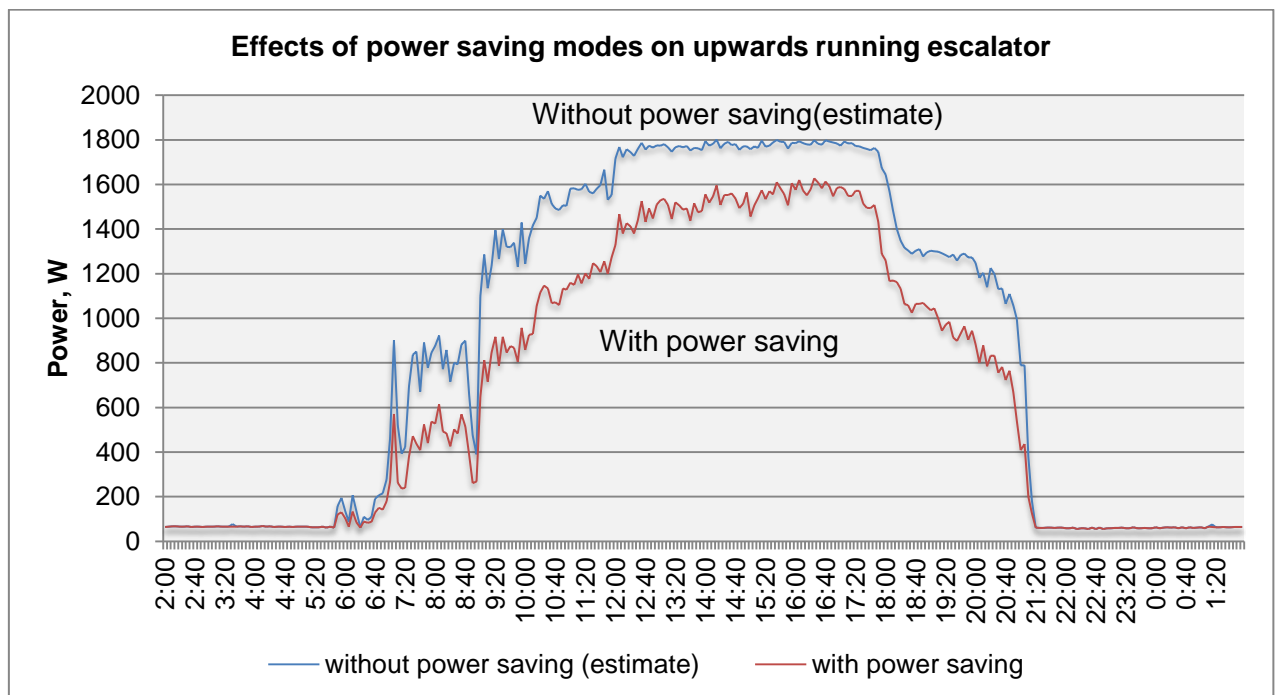


Figure 46: Comparison of electric energy consumption with and without power saving modes on upwards running escalator.

In order to make calculations, it was assumed that the escalator was continuously running so that it is possible to compare its projected power consumption to the actual measured with existing power saving modes.

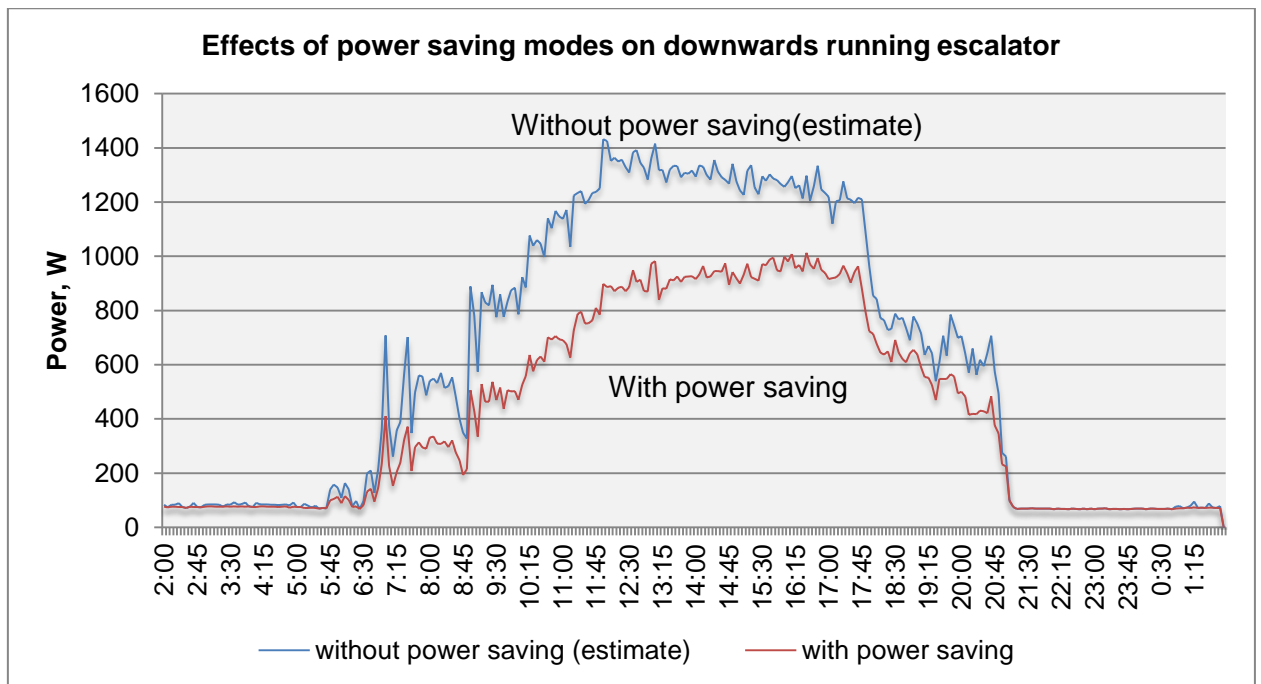


Figure 47: Comparison of electric energy consumption with and without power saving modes on downwards running escalators.

Figure 47 shows the comparison of electricity consumption of the downwards moving escalator with and without power saving modes. The calculated estimate shows that saving modes on the downwards moving escalator help to save about 28,3% of electricity consumption. Additionally, the projected curve of electricity consumption of the downwards moving escalator shows that one of the effects of the saving modes is shifting of the curve peak, which takes place when less passengers use the escalator.

4.7 Estimation of fixed losses on different escalator types

As mentioned earlier (Section 2.6), in paper [17], two escalators were compared. Valmet escalator is a continuously moving escalator, while KONE escalator had some energy saving features, such as slow-speed mode.

While trying to estimate the fixed power consumption, scatter diagrams of power consumption in comparison to passengers in five-minute sections were plotted, see Figures 48, 49. These figures were plotted using the data collected during original measurements.

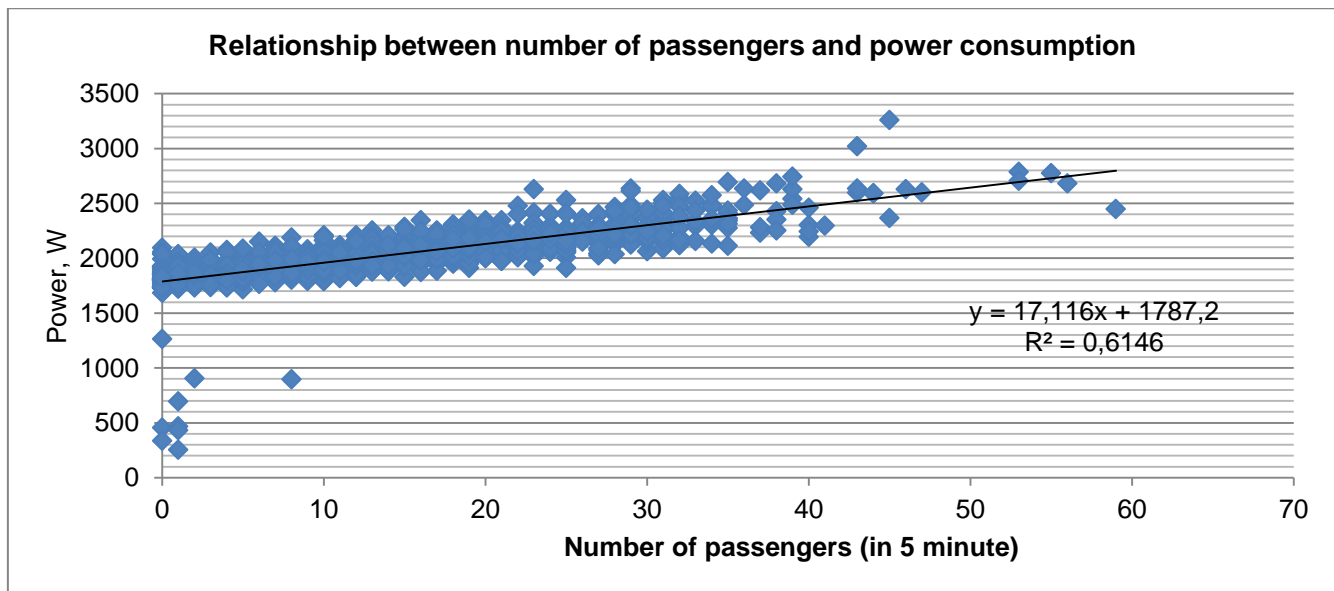


Figure 48: Scatter diagram of power vs passenger data for Valmet escalator.

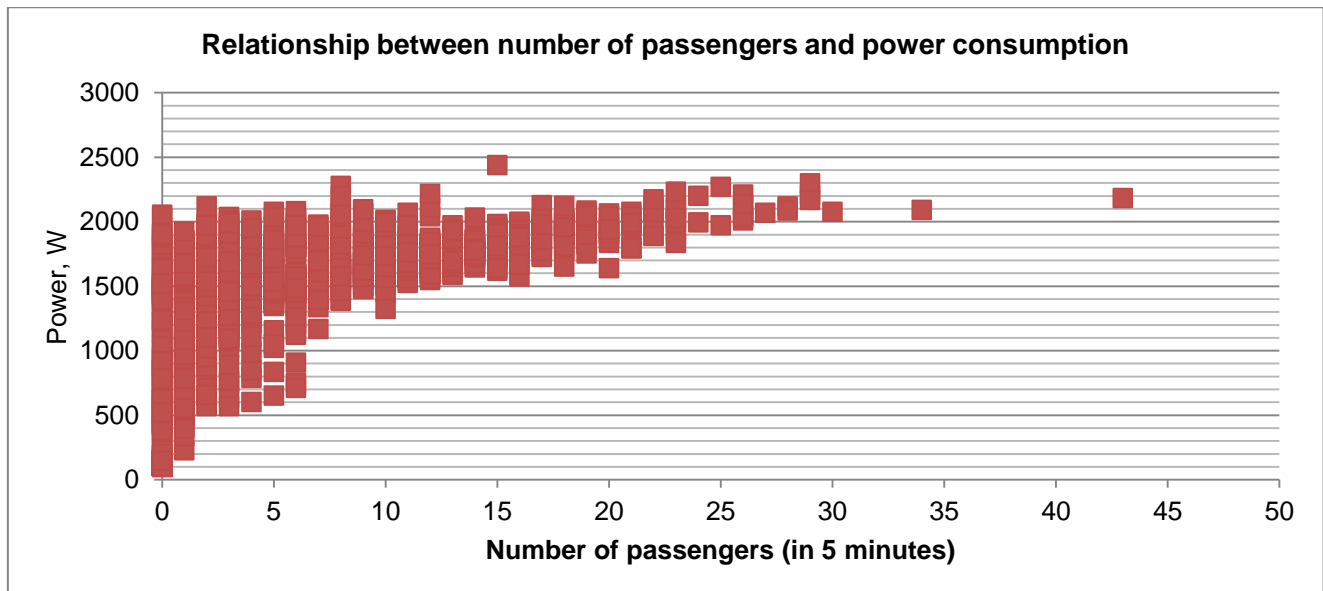


Figure 49: Scatter diagram of power vs passenger data for Kone escalator, equipped with energy saving modes.

It turns out that when the time between passengers exceeds a certain amount, for TM110 in thesis it is 30 seconds, the escalator switches into slow speed mode of around 0,2 m/s and, therefore, draws smaller amounts of power. Needless to say these speed changes affect average values of power consumption, and in the regions of up to 7 people the regression is no longer linear; therefore, same method of deriving fixed losses, as mentioned in Section 2.2.1, cannot be used.

Perhaps the formula should take into consideration the time that escalator spends in energy saving modes and should look somewhat like this:

$$E_f = (C_1 r_e + C_2) h_{nominal} + (C_3 r_e + C_4) h_{slow} + (C_5 r_e + C_6) h_{stop}; \quad (10)$$

Where, $C_1, C_2, C_3, C_4, C_5, C_6$ are coefficients depending on the mechanical design, r_e -the vertical rise and $h_{nominal}, h_{slow}, h_{stop}$ - Is the time that escalator is running with nominal speed, slow-speed mode and the time that it is stopped.

One way to get values of those coefficients might be to actually measure different escalators with different design and make a power vs rise comparison for each mode.

5. Discussion

This chapter concludes obstacles that were faced after acquisition of measurement results, further work projections and general barriers for penetration of energy efficiency systems.

A simplified model could be created where output is power consumption and input is the traffic density or time between consecutive passengers. Such a model could help to study the effects of the power saving modes on power consumption profiles and help to predict the consumption in different situations. In addition, it would be helpful to compare the results with energy calculation tools for Escalators, where available. Furthermore, it would benefit to study the adaptive control of escalator power saving modes. The idea is to optimize the times required for an escalator to switch to one of its power saving modes during different parts of the day. A comparison of optimized modes can be created and evaluation of necessity of such control system produced.

Annual power consumption estimate of the escalator pair was not reasonable to produce due to the fact that the passenger flow is unknown for such a period. It would be very helpful to monitor the passenger flow for a full year to have a better understanding and possibly to use the data in the future developed model to predict energy consumption. Perhaps future measurement sites could provide necessary data to proceed with the findings.

Judging from calculation of one person impact on power consumption curve in 5-minute average, it can be concluded that inaccuracies in people counting that happened because sensor could not distinguish correctly the amount of people when they are in a large group did not affect the measurements drastically. On the other hand, the accuracy of the people counting device in situations where there were only single passengers mattered significantly, due to individual triggers having a major role in the electricity consumption profiles.

One of the minor things that could slightly affect the accuracy of people flow measurements was a blackout in the whole shopping center. It happened once during night time at the early stage of the monitoring period for this thesis. The automatic setup of the scene was done for the low lighting conditions. Therefore, a new calibration was performed when the store was again lighted and the escalator steps were moving. Despite of recalibration, the functionality and performance of the people monitoring sensor seemed to be similar in contrast to the first calibration, and results can be thought to be near same accuracy range.

Among main barriers for penetration of energy efficient technologies and ability to perform measurements on the sites as also stated in [5], [3]:

- Lack of awareness of building owners, managers in private companies and public authorities mainly because the share of energy costs and consumption are usually low and additional investments in energy efficiency do not affect the core business.

- Lack of information about energy consumption patterns provokes poor assessment of possibility of installation energy saving measures and their profitability.
- Large costs of gathering and assessment of information regarding energy saving potentials. This also includes costs to negotiate with suppliers, installers and others.
- In most cases, the energy monitoring equipment installed does not diversify between different appliances and energy measurements of escalators or elevators are not separated from others.

It is necessary to understand that installation of measurement equipment itself does not provide any savings, unless the information is used for comparison with other consumer appliances in order to make changes towards more energy savings.

6. Conclusions

This chapter concludes final outcomes and conclusions.

One of the largest obstacles in understanding the energy consumption profiles is the presence of power saving modes on the escalator. In our situation, where the people flow is not as massive as in the public transportation environment, and especially at times of low passenger traffic, it turned out that the shape of power consumption profile is highly affected by work of power saving modes of the escalator. Due to small amounts of passengers, the 1-minute power profiles are not as descriptive as 5-minute average profiles. In our situation, of low traffic, most of the power is drawn by the fixed power consumption component. The effect of variable power consumption of each passenger on the 5-minute average power profile has been calculated and turned out to be insignificant in contrast to the fixed power consumption. In the case of a continuously moving escalator, the fixed power consumption would be constant and power consumption profile is shaped with the variable consumption component, which basically depends on the amount of passengers. In an intermittent escalator with low passenger flow, the shape of the power consumption profile is achieved by variability of the fixed power consumption component, which happens due to power saving modes. This is the reason of so unexpected results of downwards moving escalator power consumption profiles. It turns out that the passenger flow is so intermittent, that time between consecutive passengers enables the power saving modes often enough to reduce the power consumption during low traffic parts of the day to values even less than at times when there are more passengers with a more constant traffic flow.

Measurements revealed that the share of usage of upwards moving escalator from the escalator pair was 60 per cent, but in comparison to the total electricity consumption of the store, each of them was relatively small. Electricity consumption of the escalator pair altogether turned out to be only 5% of the total store consumption.

Impact of power saving technologies on electricity consumption of escalator was calculated to be around 21% for the upwards moving escalator and 28% for the downwards moving. As discussed earlier, modeling and further research might help to get a better understanding on the impacts of power saving modes of escalators and provide additional possibilities for optimization of those modes in order to increase the saving potential in various situations.

Number of starts affects the power consumption in such a way, that every time the escalator accelerates from the starting mode it consumes more power, compared to acceleration from the slow-speed mode due to speed difference of these modes and necessity to overcome starting friction. The mutual effects of acceleration and deceleration for starting and slow-speed modes on electrical energy consumption are respectively 1,98 Wh and 0,5 Wh. Consequently, the number of starts of the escalator during the day affects total electrical energy consumption of the escalator pair. Ultimately, number of starts again depends on the frequency of passenger flow and its overall pattern. The energy consumed by this acceleration period is minor, as was the effect of walking in the studied escalator pair to the overall electricity consumption. The

highest ratio of consumption is clearly dedicated to fixed losses, such as friction and inefficiencies of the drive system, due to low people flow nature of the studied escalator pair.

References

- [1] L. Ryan and N. Campbell, "Spreading the net: The multiple benefits of energy efficiency ," 2012. [Online]. Available: http://www.iea.org/publications/insights/ee_improvements.pdf. [Accessed 20 02 2015].
- [2] E. E. a. Management, "Climate and Energy 20/20/20 Targets of the European Union and the failure of energy efficiency objectives," 2013. [Online]. Available: <https://is.upc.edu/seminaris-i-jornades/seminaris/std-2013/documents/case-studies/climate-and-energy-20-20-20-targets-of-the-european-union-and-the-failure-of-energy-efficiency-objectives>. [Accessed 20 02 2015].
- [3] C. Patrao, J. Fong, L. Rivet and A. d. Almeida, "Energy efficient elevators and escalators," in *ECEEE 2009 Summer Study*, 2009.
- [4] C. Patrao, A. D. Almeida, J. Fong and F. Ferreira, "Elevators and Escalators Energy Performance Analysis," in *ACEEE Summer Study on Energy Efficiency in Buildings*, 2010.
- [5] A. D. Almeida, S. Hirzel, C. Patrao, J. fong and E. Dutschke, "Energy-efficient elevators and escalators in Europe: An analysis of energy efficiency potentials and policy measures," *Energy and Buildings*, no. 47, pp. 151-158, 2012.
- [6] "KONE Escalators and Autowalks Planning Guide," 2010. [Online]. Available: <http://cdn.kone.com/www.kone.ca/en/Images/kone-escalator-autowalk-planning-guide.pdf?v=1>. [Accessed 1 03 2015].
- [7] "Escalators Basic Components – Part Two," www.electrical-knowhow.com, 2013. [Online]. Available: <http://www.electrical-knowhow.com/2012/04/escalators-basic-components-part-two.html>. [Accessed 26 02 2015].
- [8] A. d. Almeida, "E4, Energy-Efficient Elevators and Escalators, WP 3: Report with the results of the monitoring campaign," Coimbra, 2010.
- [9] L. Al-Sharif, "Modelling of escalator energy consumption," *Energy and Buildings*, no. 43, pp. 1382-1391, 2011.
- [10] L. Al-Sharif, "Experimental Investigation into the Effect of Mechanical Design of an Escalator and Passenger Loading on its Energy Consumption," in *World Congress on Engineering*, London, 2008.
- [11] Y. Y, "Eco-efficiency trends in china, 1978-2010: Decoupling environmental pressure from economic growth.," *Ecological Indicators*, vol. 24, pp. 177-184, 2013.
- [12] K. C. C. Nefield, C. K. W. Eric and C. K. W. Kelvin, "Energy Efficient Technologies for Railway Escalators," in *ICRE*, 2008.
- [13] "Kone Eco-Efficient Solutions, Escalators," 2010. [Online]. Available: <http://cdn.kone.com/www.kone.cz/Images/eco-efficient-factsheet-escalators.pdf?v=2>.

[Accessed 17 02 2015].

- [14] "What is a carbon footprint?," [Online]. Available: <http://www.carbontrust.com/client-services/footprinting/footprint-measurement>. [Accessed 24 07 2009].
- [15] "Energy Efficiency, Infrared beams," 2006. [Online]. Available: http://www.hk-phy.org/energy/commercial/auto_phy03_e.html. [Accessed 20 02 2015].
- [16] K. C. C. Nefield and S. L. Ho, "Energy optimization of public service escalators," in *9th IET International Conference on Advances in Power System Control, Operation and Management (APSCOM 2012)*, Hong Kong, 2012.
- [17] J. Kuutti, R. E. Sepponen and P. Saarikko, "Escalator Power Consumption Compared to Pedestrian Counting Data," in *International Conference on Applied Electronics (AE)*, Pilsen, 2013.
- [18] "HuperLab 2D People Counter," HuperLab, [Online]. Available: <http://www.huperlab.com/english/product/2Dcounter/2dcounter.htm>. [Accessed 17 02 2015].
- [19] "Xovis PT3 Sensor," Xovis, [Online]. Available: <http://www.xovis.com/en/index.php?page=361>. [Accessed 17 02 2015].
- [20] "MatGuard Mats," Rockwell Automation, [Online]. Available: <http://www.ab.com/en/epub/catalogs/3377539/5866177/3377569/3383635/7611839/>. [Accessed 17 02 2015].
- [21] H. Douglas, ""piezoelectric"," Online Etymology Dictionary, [Online]. Available: <http://www.etymonline.com/index.php?term=piezoelectric>. [Accessed 17 02 2015].
- [22] *Energy performance of lifts, escalators and moving walks. Part 1: Energy measurement and verification. ISO 25745-1*, 2012.
- [23] A. T. d. Almeida, C. Patrão, J. Fong, U. Nunes and R. Araújo, "E4, Energy Efficient Elevators and Escalators, WP4: Estimation of savings," Coimbra, 2010.
- [24] J. J. Fruin, *Pedestrian planning and design*, New York, USA: Metropolitan association of urban designers, 1971.
- [25] T. Fujiyama and N. Tyler, *An Explicit Study on Walking Speeds of Pedestrians on Stairs*, London, United Kingdom: Centre for Transport Studies, University College, 2004.
- [26] J. M. Andrews and J. V. J. Boyes, *Pedestrian Movement at Victoria Underground Station*, London: University College, 1977/1978.
- [27] *Electromagnetic compatibility (EMC) Part 4-30: Testing and measurement techniques - Power quality measurement methods, IEC 61000-4-30*, 2009.
- [28] *1760 Power Quality Recorder Users Manual*, Everett, Washington, USA: Fluke Corporation, 2006.

- [29] T. Tukia, *Determining and modeling the energy*, Masters Thesis, Espoo, Finland, 2014.
- [30] *3-phase Energy and Power Meters, S0 Impulse-Logger, M-Bus Logger, EMU Electronic AG*, Baar: Switzerland.
- [31] C. M. GmbH, *Celsa Catalogue*.
- [32] "Escalator Designer for KONE TravelMaster 110," Kone, [Online]. Available: http://major-projects.kone.com/shared/tools/escalator-designer/TravelMaster_110.html. [Accessed 17 02 2015].

Appendix A

The following table provides details about the tests carried out, specifying masses, power and energy consumption over the time it was transported on top.

Tables for load impact section 4.3

Table 6: Load impact for upwards escalator.

persons masses, respectively, kg		88,72	mass value, kg		10, 10
test	mass, total, kg		power, W	energy, Wh	
1 person	88		326,4	1,45	
1 person + mass	98		361,4	1,61	
1 person + 2x mass	108		406,2	1,81	
2 persons	160		593,05	2,64	
2 persons + mass	170		623,9	2,77	
2 persons + 2x mass	180		658,4	2,93	
1 person + 1 boarding	160				
1 person + mass + 1 boarding	170				
1 person walking	88		331,129	1,39	
1 person walking + 2x mass	108		387,3	1,62	
1 walking + 1 standing	160		576,85	2,42	

Table 7: Load impact for downwards escalator.

persons masses, respectively, kg		88,72	mass value, kg		10, 10
test	mass, total, kg		power, W	energy, Wh	
1 person	88		-314,25	-1,32	
1 person + mass	98		-349,25	-1,46	
1 person + 2x mass	108		-391,05	-1,64	
2 persons	160		-547,25	-2,30	
2 persons + mass	170		-616,35	-2,59	
2 persons + 2x mass	180		-637,1	-2,67	
1 person + 1 boarding	160				
1 person + mass + 1 boarding	170				
1 person walking	88				
1 person walking + mass	108				
1 walking + 1 standing	160				